

# **Data Structures and Reduction Techniques for Fire Tests**

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## **Abstract**

To perform fire engineering analysis, data on how an object or group of objects burn is almost always needed. This data should be collected and stored in a logical and complete fashion to allow for meaningful analysis later. This thesis details the design of a new fire test Data Base Management System (DBMS) termed UCFIRE which was built to overcome the limitations of existing fire test DBMS and was based primarily on the FDMS 2.0 and FIREBASEXML specifications. The UCFIRE DBMS is currently the most comprehensive and extensible DBMS available in the fire engineering community and can store the following test types: Cone Calorimeter, Furniture Calorimeter, Room/Corner Test, LIFT and Ignitability Apparatus Tests.

Any data reduction which is performed on this fire test data should be done in an entirely mechanistic fashion rather than rely on human intuition which is subjective. Currently no other DBMS allows for the semi-automation of the data reduction process. A number of pertinent data reduction algorithms were investigated and incorporated into the UCFIRE DBMS. An ASP.NET Web Service (WEBFIRE) was built to reduce the bandwidth required to exchange fire test information between the UCFIRE DBMS and a UCFIRE document stored on a web server.

A number of Mass Loss Rate (MLR) algorithms were investigated and it was found that the Savitzky-Golay filtering algorithm offered the best performance. This algorithm had to be further modified to autonomously filter other noisy events that occurred during the fire tests. This algorithm was then evaluated on test data from exemplar Furniture Calorimeter and Cone Calorimeter tests.

The LIFT test standard (ASTM E 1321-97a) requires its ignition and flame spread data to be scrutinised but does not state how to do this. To meet these requirements the fundamentals of linear regression were reviewed and an algorithm to mechanistically scrutinise ignition and flame spread data was developed. This algorithm seemed to produce reasonable results when used on exemplar ignition and flame spread test data.

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## List of Abbreviations and Terminology

BFRL	Building and Fire Research Laboratory
CFD	Computational Fluid Dynamics
CFAST	Consolidated Model of Fire and Smoke Transport
DBMS	Data Base Management System
DISTANCE	Distance from a reference point (m)
EXTCOEFF	Extinction coefficient ( $\text{m}^{-1}$ )
fCO	Gas yield of CO (kg/kg)
fCO <sub>2</sub>	Gas yield of CO <sub>2</sub> (kg/kg)
FDMS	Fire Data Management System
FDS	Fire Dynamics Simulator
fH <sub>2</sub> O	Gas yield of H <sub>2</sub> O (kg/kg)
fHBR	Gas yield of HBR (kg/kg)
fHCL	Gas yield of HCL (kg/kg)
fHCN	Gas yield of HCN (kg/kg)
FLAMEFRONT	Position of the flame front (m)
FLUX	Heat flux ( $\text{kW/m}^2$ )
FRIS	Fire Research Information Service
fSOOT	Gas yield of Soot (kg/kg)
GOF	Goodness of Fit
HC	Effective Heat of Combustion (MJ/kg)
HCPUA	Effective Heat of Combustion Per Unit Area ( $\text{MJ/kg.m}^2$ )
HRR	Heat Release Rate (kW)
HRRPUA	Heat Release Rate Per Unit Area ( $\text{kW/m}^2$ )
HRRTOT	Total heat released (MJ)
HRRTOTPUA	Total heat released per unit area ( $\text{MJ/m}^2$ )
LIFT	Lateral Ignition and Flame Spread Test
MASS	Mass of the specimen (kg)
MASSFLOW	Mass flow rate (kg/s)
MLR	Mass Loss Rate (kg/s)
MLRPUA	Mass Loss Rate Per Unit Area ( $\text{kg/s.m}^2$ )
MRE	Mean Residual Error (-)

NIST	National Institute of Standards and Technology
OPTICALDENSITY	Optical density of smoke ( $\text{m}^{-1}$ )
PRESSURE	Pressure difference (Pa)
RHS	Right Hand Side
RSR	Rate of Smoke Released ( $\text{m}^2/\text{s}$ )
SEA	Specific Extinction Area ( $\text{m}^2/\text{kg}$ )
TSR	Total Smoke Released ( $\text{m}^2$ )
TIME	Time (s)
TEMPERATURE	Temperature measurement (K)
UI	User Interface
VOLFLOW	Volumetric flow rate ( $\text{m}^3/\text{s}$ )
XCO	Mole fraction of CO (-)
XCO2	Mole fraction of $\text{CO}_2$ (-)
XH2O	Mole fraction of $\text{H}_2\text{O}$ (-)
XHBR	Mole fraction of HBR (-)
XHCL	Mole fraction of HCL (-)
XHCN	Mole fraction of HCN (-)
XML	eXtensible Markup Language
XSLT	Extensible Stylesheet Transformation Language
XSOOT	Mole fraction of Soot (-)
XNOX	Mole fraction of $\text{NO}_x$ (-)
XO2	Mole fraction of $\text{O}_2$ (-)
ZM	Zero Mean

## List of Mathematical Symbols

$\beta_0$	= First parameter of the model $Y$ .
$\beta_1$	= Second parameter of the model $Y$ .
$b$	= Ignition correlation parameter ( $s^{-1/2}$ ).
$b_0$	= Estimate of parameter $\beta_0$ .
$b_1$	= Estimate of parameter $\beta_1$ .
$c$	= The specific heat of the material (J/kg/K).
$C$	= Flame heat transfer parameter ( $s^{1/2}m^{3/2}kW^{-1}$ ).
$\varepsilon$	= Random error term.
$\hat{\varepsilon}$	= Residual error term.
$F(t)$	= Thermal response function (-).
$F(x)$	= Surface flux configuration invariant ( $(kW/m^2)/mV$ ).
$\Delta P$	= The orifice meter pressure differential (Pa).
$\Delta h_c$	= Net heat of combustion (kJ/kg).
$h_c$	= Convection coefficient ( $W/m^2$ ).
$h$	= Heat loss coefficient ( $kW/m^2K$ ).
$\kappa$	= Calibration constant for oxygen consumption analysis ( $m^{1/2}kg^{1/2}K^{1/2}$ ).
$k\rho c$	= Thermal heating property ( $kW/m^2K$ ) <sup>2</sup> s.
$L_o$	= Thickness of material (m).
$\Phi$	= Flame heating parameter ( $kW^2m^{-3}$ ).
$\dot{Q}(t)$	= Heat release rate (kW).
$\dot{q}_{ig}''$	= Flux applied to a specimen ( $kW/m^2$ ).
$\dot{q}_{ig,min}''$	= Minimum heat flux required for ignition ( $kW/m^2$ ).
$\dot{q}_{crit}''$	= Critical heat flux required for ignition ( $kW/m^2$ ).
$\dot{q}_{s,min}''$	= Minimum flux required for flame spread ( $kW/m^2$ ).
$\dot{q}_e''$	= Measured incident flux ( $kW/m^2$ ).
$\dot{q}_{e(50mm)}''$	= Flux at 50 mm ( $kW/m^2$ ).
$\rho$	= Density of the specimen ( $kg/m^3$ ).

$r_0$	= Stoichiometric oxygen/fuel ratio (-).
$R^2$	= Measure of the Goodness of Fit of a line.
$S$	= Sum of squares of the deviations from the true line $Y$ .
$\sigma$	= Stefan-Boltzman constant ( $\text{W/m}^2 \cdot \text{K}^4$ ).
$t$	= Time (s).
$t^*$	= Characteristic equilibrium time (s).
$t_{ig}$	= Time to ignition (s).
$T_\infty$	= Ambient temperature (K).
$T_e$	= Absolute temperature of the gas at the orifice meter (K).
$T_{ig}$	= Ignition temperature (K).
$T_s$	= Surface temperature of the semi infinite solid (K).
$T_{s,\min}$	= Minimum temperature necessary for flame spread (K).
$X_{O_2(t)}$	= Mole fraction of oxygen in the exhaust duct before delay time correction (-).
$X_{O_2(t)}^0$	= Mole fraction of oxygen in the analyser (-).
$V$	= Three point average of the flame front velocity (m/s).
$\hat{Y}$	= Estimate of the model $Y$ .

# 1 Introduction

To perform fire engineering analysis data on how an object or group of objects burn is almost always needed. This data should be collected and stored away in a logical and complete fashion to allow for meaningful analysis later. Any data reduction which is performed on this data should be done in an entirely mechanistic fashion rather than rely on human intuition, which is subjective.

To make use of these existing Data Base Management Systems (DBMS) the raw fire test data must be manually reduced to meaningful quantities and converted into a format suitable for storage within the specified DBMS. This process is time consuming and error prone so it was decided to create a new DBMS specification called UCFIRE which will also provide tools to automate the data reduction and storage processes. Another goal of the UCFIRE DBMS is to allow open access to this high quality fire test data in the most efficient and useful manner.

## 1.1 Existing DBMS

The new UCFIRE DBMS specification will be based on the successes of publicly available fire test DBMS and will seek to extend beyond their limitations. These publicly available DBMS include:

- National Institute of Standards and Technology (NIST) [1] Online Portals
  - The Fire Research Information Service (FRIS) [2]
  - Fire on the Web [3]
  - Fire and Building Educational Resource Collection (FABERC) [4]
- SP Fire Database [5]
- Fire simulation software databases
  - FDS 4 [6]
  - BRANZFIRE [7]
  - CFAST [8]
- Fire Data Management System
  - FDMS 1.0 [9]
  - FDMS 2.0 [10]

- FIREBASEXML [11]

## **1.2 Software Development Tools**

With an emphasis on usability and usefulness the UCFIRE DBMS will require many powerful features such as the ability to display graphs and images, play movies, and access data both locally and over the internet. This set of programs must also be relatively easy to code as the focus of the research is the data structure of the DBMS and the data reduction algorithms, not coding.

After some consideration Visual Basic.NET 2005 was chosen as the development platform for the following reasons:

- Visual Basic.NET has a large number of tools for designing forms - the basic graphical User Interface for programs.
- Visual Basic.NET has a simple and easy to read syntax.
- There is a lot of support on the internet for programming in Visual Basic.NET.
- Visual Basic.NET has native support for XML.
- Visual Basic.NET applications are easily integrated with the internet.

For a more detailed treatment of Visual Basic.NET refer to *Professional Visual Basic 2005* [12].

## **1.3 eXtensible Markup Language (XML)**

The eXtensible Markup Language (XML) is a computer language that is used to store data in a structured format that both humans and computers can understand. An XML document is a structured collection of elements; starting at a root element (the first element) and branching out to contain a number of other elements and variables. The XML data structure offers many advantages and both the FIREBASEXML DBMS and the new UCFIRE DBMS store their fire test data in XML. Some advantages of using XML include:

- The names of the XML elements are arbitrary and therefore XML can have a virtually unlimited number of unique elements making it ideal for use as a DBMS.
- For a DBMS to be effective the integrity of its data must be ensured and so the data structure of this DBMS is defined by another document called an XML schema. An XML document can be easily validated by comparing its structure and content with that defined by the XML schema thus ensuring the integrity of the DBMS.
- The structure of an XML document conforming to one particular schema may be transformed by a single step method so that its structure conforms to another dissimilar schema. This transformation is described by a separate document with the eXtensible Stylesheet Language Transformation (XSLT) specification. This process could be extremely useful if the user wished to easily and efficiently export data from the fire test DBMS directly into fire simulation software.

For a more detailed treatment of XML refer to *Professional XML* [13] and for a more detailed treatment of the XSLT transformation process please refer to *XSLT 2.0 Programmer's Reference* [14].

## **1.4 Web Interfaces to Databases**

It is imperative that fire test data produced at the University of Canterbury and stored within the UCFIRE DBMS be readily available to interested parties in the community to maximise its usefulness. A user could theoretically download an entire UCFIRE document, containing multiple fire tests from the University of Canterbury web server, every time they wished to access a single fire test but this is the most inefficient method of providing access to the data. Preferable the user's UCFIRE client should be able to make a request for a single fire test to a program running on the University of Canterbury's web server, and only the pertinent information should be sent to the user's computer to minimise download times. Applications that run on web servers and respond to client requests are termed Web Services within the .NET



framework. For a more detailed treatment of Web Services refer to *Professional Visual Basic 2005* [12].

## **1.5 Research Objectives**

The main aim of this research is to create a data reduction tool that will automatically process fire test data in a systematic way, store it in a logical and complete fashion and allow for researchers to make further use of this data. To achieve this aim, the research is separated into four steps:

- Investigate current fire test database formats and relevant fire test standards to find the best way of storing this data.
- To create a semi-automated data reduction application using software development tools that will process and store the fire test data.
- Investigate and validate data reduction algorithms necessary to perform the relevant analysis.
- Create an ASP.NET Web Service that will allow interested parties to access the database's information from across the internet.

## **1.6 Report Structure and Outline**

Chapter 2 investigates the purpose and data structure of existing fire test DBMS. This chapter will highlight the strengths and weakness of each DBMS and how it may contribute to the UCFIRE DBMS.

Chapter 3 investigates the storage requirements of relevant fire test standards. Chapter 4 outlines the proposed format of the UCFIRE data structure. Chapter 5 validates the UCFIRE data structure against standard test requirements for a variety of fire tests.

The structure of the Microsoft Excel file which will contain the unprocessed fire test data will be explored in Chapter 6.

Chapter 7 is concerned with the algorithms required to reduce data from Cone Calorimeter, Furniture Calorimeter, Room/corner, LIFT and Ignitability Apparatus tests.

Chapters 8, 9 and 10 describe the motivation, and methods used, to scrutinise LIFT ignition and flame spread data. These three chapters are only applicable to the LIFT test.

The User Interface for the UCFIRE DBMS and the methodology for integrating this User Interface to the internet with the Web Service WEBFIRE are described in Chapter 11 of this thesis.

Chapter 12 summarizes all the findings of this thesis and make recommendations for further study.

## **2 Existing Data Structures for Fire Tests**

The new UCFIRE DBMS specification will be based on the successes of publicly available fire test DBMSs and will seek to solve their limitations. These publicly available DBMSs include:

- National Institute of Standards and Technology (NIST) [1] Online Portals
  - The Fire Research Information Service (FRIS) [2]
  - Fire on the Web [3]
  - Fire and Building Educational Resource Collection (FABERC) [4]
- SP Fire Database [5]
- Fire simulation software databases
  - FDS 4 [6]
  - BRANZFIRE [7]
  - CFAST [8]
- Fire Data Management System
  - FDMS 1.0 [9]
  - FDMS 2.0 [10]
- FIREBASEXML [11]

This chapter will analyse the purposes, advantages and disadvantages of these various DBMS and how they can contribute to the new UCFIRE DBMS specification.

### ***2.1 NIST Related Online Electronic Resources***

The NIST Related Online Electronic Resources are separate publicly available electronic resources that the National Institute of Technology and Standards (NIST) have contributed to. These include

- The Fire Research Information Service (FRIS) [2]
- Fire on the Web [3]
- Fire and Building Educational Resource Collection (FABERC) [4]

### **2.1.1 The Fire Research Information Service (FRIS)**

The Fire Research Information Service (FRIS) [2] is a large collection of information on fire and building research topics that has been collected by Building and Fire Research Laboratory (BFRL) Research Information Services located at NIST. The purpose of FRIS [2] is to be a *“vast collection of information on nearly any fire research related subject that has been gathered from both BFRL staff members, as well as researchers, fire protection engineers, and scientists from around the world.”*

This site contains links to the following online resources:

- FRIS publications (FIREDOC).
- Fire on the Web (To be explained in Chapter 2.1.2).
- BFRL Software.
- Fire Safety Fact Sheets containing information for people living in manufactured housing.
- An online newsletter (Fire.Gov).
- Information on available fire research grants.
- FABERC (To be explained in Chapter 2.1.3).
- BFRL Online Publications from the year 1993 onwards.
- Information on the National Earthquake Hazards Reduction Program.

### **2.1.2 Fire on the Web**

Fire on the Web [3] is a collection of information from the Building and Fire Research Laboratory (BFRL) Research Laboratory's Fire Research Division at NIST. The purpose of Fire on the Web is to be a publicly available collection of fire related software, experimental fire data and movies of fire tests produced by the Building and Fire Research Laboratory's Fire Research Division at NIST.

This web site contains links to the following online resources:

- Test Data:
  - A collection of fire test experimental results including video clips, pictures and graphs.
  - A collection of experimental results for hydrocarbon diffusion flames experiments.
  - A collection of images and movies for fire sprinkler tests.
  - Measured data presented as graphs for smoke alarms tests.
  - Reports containing data on industry sponsored passenger train fire tests.
  - A collection of images and movies for fire fighting agents' tests.
  - A comprehensive set of experimental and fire simulation results for wild land-urban interface and wild land fires.
  - A collection of fire tests stored in FDMS 2.0 format. The FMDS 2.0 format will be described later in Chapter 2.4.
- Software models:
  - The computational fluid and fire dynamics model - Fire Dynamics Simulator (FDS 4).
  - Smoke plume trajectory model (ALOFT-FT).
  - Zone models (CFAST/FAST).
  - BFRL's collection of fire related software.
- Other:
  - A collection of videos on the progression of Christmas tree fires.
  - An online newsletter (Fire.Gov).

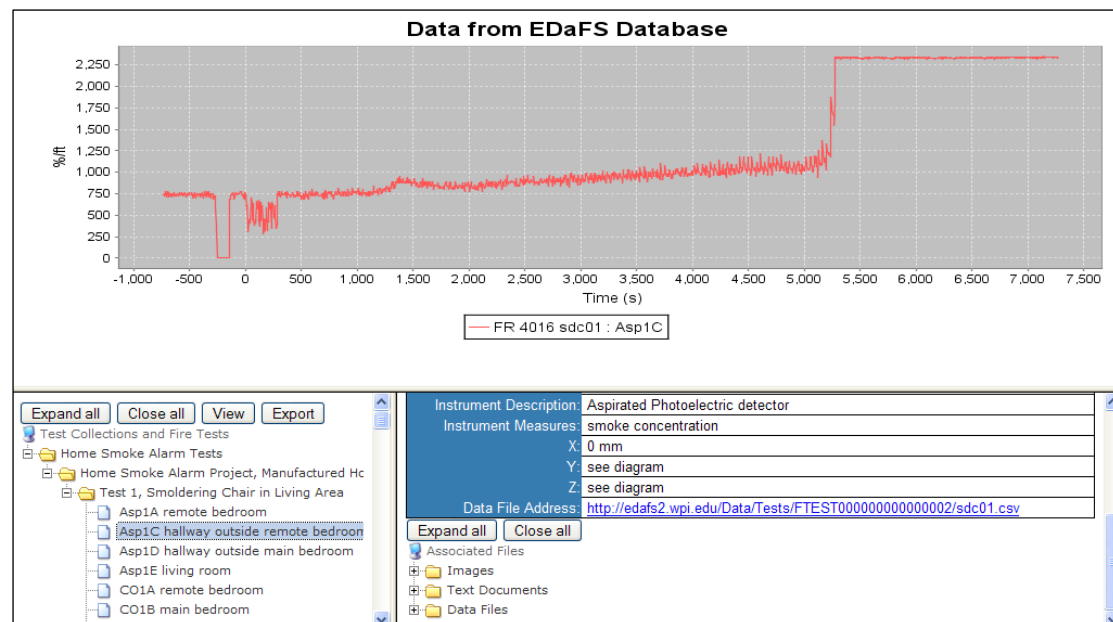
### **2.1.3 FABRC**

The National Institute of Standards and Technology (NIST) and the National Science Foundation are developing an online portal to a database of fire resources. The purpose of this electronic resource is to be a widely available and easily accessed collection of fire science and building research resources. This portal is called Fire and Building Educational Resource Collection (FABERC) [4] and will contain the following resources:

- Fire Test Data.

- NIST/BFRL Publications.
- NIST/BFRL Video and Image Collection.
- TYCO Fire Multimedia Collection.
- Virtual Reality Sprinkler Images.
- Journal of Fire Protection Engineering Publications.
- SFPE Instructional Collection.

This online portal is still in the developmental stage and there are currently only 2 fire test experiments stored on this website. A screen shot of fire test data stored on this online portal can be seen in Figure 1.



**Figure 1: Screen Shot of FABERC**

## 2.1.4 Limitations of NIST Related Online Electronic Resources

A number of limitations may be drawn from the inspection of these online portals:

- There seems to be a substantial amount of overlap between the three NIST sponsored online portals: for instance, they all seem to reference the NIST/BRL publications.
- The fire test portion of the websites seems to be incomplete and unstructured. While data stored on Fire on the Web website is in the FDMS 2.0 format (to

be described in Chapter 2.4) the online portal seems to hide some of the details of the tests.

- The data structure used to store data on the FABERIC website has not been specified.
- It is not possible to directly perform additional analysis on the fire test's data for any of the three resources.
- The goal of these electronic resources seems to be to gather a vast collection of resources related to fire engineering research together on one site and this seems to dilute the usefulness of each individual resource. For instance more time could be spent on developing an interface that allows users to further analyse and the reduce fire test data stored in the online databases.

## 2.2 SP Fire Database

The Fire and Protection Department of SP Technical Research Institute of Sweden [5] has developed an online database containing data from fire tests that they have performed. A user is prompted for search criteria to search the database with and then a list of fire test items matching the search criteria is returned such as that shown in Figure 2.

ImportID	Material	Material2	Product Object	Scenario Method	Reference	Show XML	Text	Graph
660	Fabric: 100% Polyester ; Interliner: Polyester fibre	Polyether foam	CBUF 1:04 Upholstered chair	Furniture full-scale calorimeter (CBUF)	CBUF - Fire Safety of Upholstered Furniture, EC Report EUR 16477 EN, contact SP for more information.	Show	Export	Export Draw
661	Fabric: 100% acrylic pile fabric/FR back coated/ cellulosic ground ; Interliner: FR polyester fibre	CMHR foam/seat FR polyester interior back	CBUF 1:05 Upholstered chair	Furniture full-scale calorimeter (CBUF)	CBUF - Fire Safety of Upholstered Furniture, EC Report EUR 16477 EN, contact SP for more information.	Show	Export	Export Draw
662	Fabric: Leather ; Interliner: Polyester fibre	HR foam	CBUF 1:06 Upholstered chair	Furniture full-scale calorimeter (CBUF)	CBUF - Fire Safety of Upholstered Furniture, EC Report EUR 16477 EN, contact SP for more information.	Show	Export	Export Draw

Figure 2: SP Database Search Results

The user is able to either to show tabulated data (Figure 3 and Figure 4), export this data to either XML or a text file, or graph it (Figure 5).

<b>Show Details</b>	
<a href="#">Back</a>	
Keyword	Value
Material	Fabric: 100% Polyester ; Interliner:Polyester fibre
Material2	Polyether foam
Product	
Object	CBUF 1:04 Upholstered chair
Scenario	
Method	Furniture full-scale calorimeter (CBUF)
Reference	CBUF - Fire Safety of Upholstered Furniture, EC Report EUR 16477 EN, contact SP for more information.
Comment	Upholstered; loose seat and back cushions
Owner	
IsPublic	1
ImportDate	2005-11-03 09:53:03

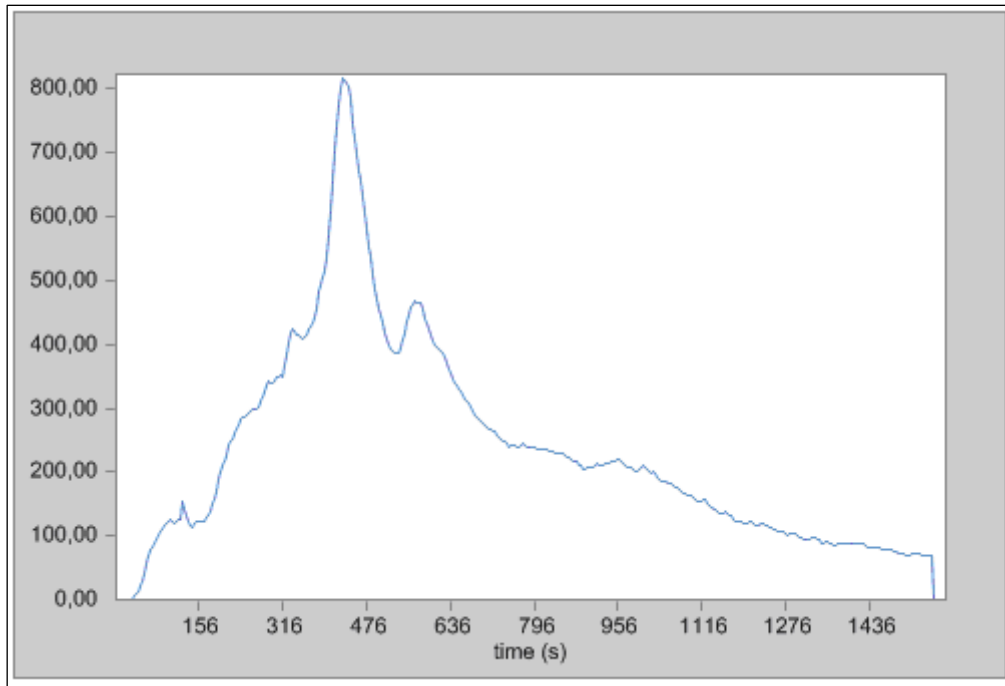
Scalar	Value
Peak heat release (kW)	815.9
Total heat release (MJ)	365.1
Initial mass (g)	28700
Total massloss (g)	25410
Average heat of combustion (MJ/kg)	14.380

Figure 3: SP Database's Tabulated Data

Time (s)	HRR (kW)	SPR (m2/s)
0	0	-2.31251806161495E-02
4	0	-2.02485416072893E-02
8	0	-1.73924565536037E-02
12	0	-1.53344376912368E-02
16	0	-1.33026117536885E-02
20	0	-9.63566093967517E-04
24	0	3.68592333804807E-02
28	.50175	8.62338881455088E-02
32	6.3651	.158759044330418
36	9.9371	.228174507089456
40	13.636	.278112486684982
44	20.905	.337121470693294
48	27.407	.551212332392086
52	42.157	.579796101259529
56	55.563	.924768264100298
60	67.825	1.02152952389607
64	77.635	1.12024392266048
68	82.084	1.23597100749598
72	89.334	1.41368996292909
76	95.641	1.45548212651704
80	100.06	1.97256474174953
84	106.68	1.91319639835802

Figure 4: SP Database's Tabulated Data





**Figure 5: Graph of HRR Data for an SP Database Item**

### **2.2.1 Limitations of the SP Fire Database**

- It is not possible to perform any additional analysis or data reduction on the information contained within the SP Fire Database.
- This DBMS can only plot one set of data per graph; it is not possible to plot multiple sets of data on the same graph.
- Contains a limited amount of information on the materials used in the fire test. This would hinder the modelling of the fire test using fire simulation software.
- This DBMS cannot smooth noisy data from fire tests.
- It would be better to export data into a more useful and accessible format for the user such as a Microsoft Excel file.

## **2.3 Fire Model Databases**

Popular fire simulation software that may be desirable to use in conjunction with a fire test DBMS are:

- The Fire Dynamics Simulator (FDS). FDS 4 is a Computational Fluid Dynamics model (CFD) program [6] developed by the National Institute of Standards and Technology (NIST) to model the transportation of heat and smoke caused by a fire. The results of FDS 4 can be visualized with an additional program also developed by NIST called Smokeview. FDS 4 was written in the FORTRAN programming language and Smokeview was written in the C/C++ programming languages.
- BRANZFIRE – is a zone model developed by BRANZ Limited [7] and is used to calculate the time varying distribution of heat, smoke, and fire gases throughout a multiple room model caused by a fire. BRANZFIRE was written using the Visual Basic programming language.
- Consolidated Model of Fire and Smoke Transport (CFAST) [8] – is a zone model developed by NIST with a .NET programming language. CFAST uses the same visualization software (Smokeview) as FDS 4.

These examples of fire simulation software all require a reservoir of data to use in their calculations.

### **2.3.1 FDS 4**

Data for FDS 4 calculations is contained in an ASCII text file called *database4*. It should be noted that version 5 of FDS has been released and it no longer contains an inbuilt database of materials. An excerpt from FDS 4's *database4* [6] can be seen in Figure 6.

Database file for FDS 4 (Version 4.0, July, 2004)

```
&REAC ID='PROPANE'
  FYI='Propane, C_3 H_8'
  MW_FUEL=44
  NU_O2=5.
  NU_CO2=3.
  NU_H2O=4.
  SOOT_YIELD=0.01 /

...

&SURF ID                      = 'PMMA'
  FYI                          = 'Quintiere, Fire Behaviour'
  RGB                          = 0.90,0.90,0.90
  HEAT_OF_VAPORIZATION         = 1620.
  HEAT_OF_COMBUSTION           = 25200.
  BURNING_RATE_MAX              = 0.028
  DELTA                        = 0.012
  KS                           = 0.19
  C_P                          = 1.42
  DENSITY                      = 1190.
  BACKING                      = 'INSULATED'
  TMPIGN                       = 380. /
```

**Figure 6: Excerpt from *database4* [6]**

This database file contains two types of data items:

- Reaction properties (REAC)
- Material properties/Surface Boundary Conditions (SURF)

The REAC data item defines parameters associated with the gas-phase reaction of oxygen and fuel [6].

The REAC data item can contain the following members [6]:

- REAC ID: This line references the reaction.
- FYI: This line contains a description of the reaction data item. This line may also include references to journal articles and other publications.
- MW\_FUEL: The molecular weight of the fuel (g/mol)
- Y\_O2\_INFTY: The ambient mass fraction of Oxygen (-).
- T\_F\_INLET: The mass fraction of fuel in the fuel stream (-).

- EPUMO2: The amount of energy released per unit mass of oxygen consumed (kJ/kg).
- RADIATIVE FRACTION. The fraction of energy released from the flame as thermal radiation.
- NU\_O2: The ideal stoichiometric coefficient for oxygen (-).
- NU\_CO2: The ideal stoichiometric coefficient for carbon dioxide (-).
- NU\_H2O: The ideal stoichiometric coefficient for water vapour (-).
- NU\_CO: The ideal stoichiometric coefficient for carbon monoxide (-).
- CO\_YIELD: The fraction of fuel mass converted into carbon monoxide (-).
- SOOT\_YIELD: The fraction of fuel mass converted into smoke particulate (-).

For instance for the PROPANE data item in *database4* (the excerpt shown in Figure 6), the ideal stoichiometric coefficient for Oxygen is 5, for Carbon Dioxide it is 3, and for Water vapour it is 4. The soot yield is 0.01 kg/kg, which is the default value, and the molecular weight of the fuel is 44 g/mol.

The SURF line defines the boundary conditions for objects within the FDS 4 model. The material that the object is composed of is defined by the SURF ID element. The different SURF data items contained within *database4* are:

- UPHOLSTERY
- CONCRETE
- GYPSUM BOARD
- CARPET
- SPRUCE
- ETHANOL
- METHANOL
- HEPTANE
- KEROSENE
- PMMA
- MARINITE
- CEILING TILE
- SHEET METAL
- PLASTIC A

- STEEL
- BRICK
- GLASS

It is not possible to have two SURF data items with the same name.

The material properties/surface boundary conditions (SURF) data item in *database4* can contain the following data elements [6]:

- SURF ID: This line references the surface boundary condition data element.
- FYI: This line contains a description of the surface boundary conditions data element. This single line may also include references to journal articles and other publications.
- ADIABATIC: With the option of 'TRUE' or 'FALSE' this data element indicates whether or not there is radiative or convective heat transfer from the gas to the material.
- BACKING: With the option of 'INSULATED' or 'EXPOSED' this data element indicates whether or not heat transfer can occur through the back of the material.
- BURNING\_RATE\_MAX: The maximum measured burning rate of the material ( $\text{kg/m}^2/\text{s}$ ).
- C\_P: The specific heat of the material ( $\text{kJ/kg.K}$ ). This data element is only for thermally-thick materials.
- C\_DELTA\_RHO: The product of the specific heat, density, and thickness of the material ( $\text{kJ/kg.K}$ ). This data element is only for thermally-thick materials.
- DELTA: The thickness of the material (m). This data element is only for thermally-thick materials.
- DENSITY: The density of the material ( $\text{kg/m}^3$ ).
- EMISSIVITY: Defines the emissivity of the material (-).
- HRRPUA: The Heat Release Rate per Unit Area ( $\text{kW/m}^2$ ).
- HEAT\_OF\_VAPOURIZATION: The amount of energy ( $\text{kJ/kg}$ ) required to vaporize the material once its surface temperature has reached TMPIGN.
- HEAT\_OF\_COMBUSTION: The heat released when the material undergoes combustion ( $\text{kJ/kg}$ ).

- KS: Thermal conductivity of the material (W/mK). This data member is only for thermally-thick materials.
- RGB: The line specifies the colour of the material as a fraction of the primary colours: red, green and blue.
- TMPIGN: The minimum surface temperature for the material to undergo ignition (°C).

Note that the difference between thermally-thick and thermally-thin materials will be described later in Chapter 3 of this thesis.

The Heat Release per Unit Area (HRRPUA) can either be defined as a scalar value or with FDS 4's step function called RAMP. The step function for material PLASTIC A of *database4* can be seen in Figure 7.

```
&SURF ID='FIRE',HRRPUA=500.0,RAMP Q='fireramp' /
&RAMP ID='fireramp',T= 0.0,F=0.0 /
&RAMP ID='fireramp',T= 1.0,F=1.0 /
&RAMP ID='fireramp',T=30.0,F=1.0 /
```

**Figure 7: FDS 4's RAMP Command**

The RAMP command defines a time varying quantity such as HRRPUA as a series of step functions. The steps are activated when the simulation reaches the time value defined by  $T$  and then sets the time varying quantity to a fraction of a predefined value. For instance the fire starts out at  $0 \text{ kW/m}^2$  at time  $T = 0 \text{ s}$  but then at time  $T = 1.0 \text{ s}$  the fire in Figure 7 reaches its full value of  $500 \text{ kW/m}^2$ .

This is a cumbersome method of defining a time series (that is a vector that is a function of time) and there are much better methods of doing so which will be discussed in later in this chapter and also in the next chapter of this thesis.

This database format is very limited in scope since the priority of this database is not to be a comprehensive collection of fire test data but rather a reservoir of necessary physical parameters to estimate the spread of fire and smoke.

### 2.3.2 BRANZFIRE

Data for BRANZFIRE's calculations are contained in two Microsoft Access File called *thermal.mbd* and *fire.mbd* and a number of ASCII text files. The data elements of *thermal.mbd* include:

- ID: This line references the material.
- Material Description: A description of the burning object.
- Thermal Conductivity: The thermal conductivity of the burning object (W/mK).
- Specific Heat: The specific heat of the burning object (kJ/kgK).
- Density: The density of the burning object (kg/m<sup>3</sup>).
- Emissivity: The emissivity of the burning object (-).
- Min Temp for Spread: The minimum temperature for flame spread (°C).
- Flame Spread Parameter: The flame spread parameter (kW<sup>2</sup>/m<sup>3</sup>).
- Cone Data File: Contains the name of the text file stored in the same directory as *thermal.mbd* that contains time series data from a cone calorimeter test.
- Comments: Contains references.
- Soot Yield: The yield of soot for the burning object (g/g).
- CO<sub>2</sub> Yield: The yield of CO<sub>2</sub> for the burning object (g/g).
- H<sub>2</sub>O Yield: The yield of H<sub>2</sub>O for the burning object (g/g).
- Calibration Factor: Contains the calibration factor for the measurements.
- Comments: Contains references.

The Cone data file contains HRR data from Cone Calorimeter tests of the specimens at different heat fluxes. An excerpt from one of these files *agedply.txt* can be seen below in Figure 8.

```
"Aged Ply"  
"Number of HRR Curves","03"  
"Heat Flux",25  
"Number of HRR Data Pairs",172  
"sec,kW/m2"  
0,30  
1.2,39.3  
6.2,100.2  
11.2,124.6  
16.2,125.2  
21.2,123.5  
26.2,117.1  
31.2,115.1  
36.2,113.5
```

**Figure 8: Excerpt from agedply.txt**

BRANZFIRE's method of defining a time series is more efficient than FDS 4 and is easier to read.

The data elements of *fire.mbd* include:

- Energy Yield: The total heat released by the burning object (MJ/kg).
- O<sub>2</sub> Yield: The yield of O<sub>2</sub> for the burning object (g/g).
- H<sub>2</sub>O Yield: The yield of H<sub>2</sub>O for the burning object (g/g).
- CO Yield: The yield of CO for the burning object (g/g).
- Fire Height: The height of the burning object (m).
- Object Type: The classification of the burning object. The classification list includes: Gas Burner, Vehicle, Furniture, t-squared Fire, and Other.
- Description: Contains a description of the burning object.
- Time – Heat Release: Time series measurements of the HRR (s, kW)
- Soot Yield: The yield of soot for the burning object (g/g).
- Max HRR: The maximum HRR reached (kW).
- Growth Rate of the t-squared fire.
- Fuel: The type of fuel the burning object is modelled as.



### 2.3.3 CFAST

Material data for CFAST's calculations is contained in a comma delimited (.CSV) file called *THERMAL.csv*. It stores the following data elements [8]:

- Name: Name of the data item.
- Description: Description of the burning object.
- Conductivity: The conductivity of the burning object (W/m/K).
- Specific heat (J/kg/K).
- Density: Density of the burning object (kg/m<sup>3</sup>).
- Thickness: Thickness of the burning object (m).
- Emissivity: Emissivity of the burning object (-).

The Zone Model CFAST does not require many parameters for its calculations and so this database is very limited in scope.

### 2.3.4 Summary

These databases are often very limited in their scope and only contain a few parameters necessary for the program to perform its calculations. Thus they could be viewed as a subset of the information contained in a fire test DBMS. They only contain exemplar data and are not intended for the long term archiving of experimental data. Thus they are not explored further as a possible storage methodology. However it does suggest that the data structure of UCFIRE should be created using XML as a single XSLT transformation could be applied to the UCFIRE document to convert a subset of its stored test data into a specific format for use with one of the fire simulation software packages.

## **2.4 FDMS 1.0 and 2.0**

The Fire DataBase Management system FDMS [9] was created by Babrauskas et al. at NIST. The purpose of FDMS was to:

- Standardize the exchange of fire test data not only between laboratories but also within the same laboratory.
- Create an application to manage this data (at the time that FDMS 1.0 was created an application to manage the fire test data had not yet been created).
- Invent a method to store vector data produced from modern fire tests. This was particularly important with the invention of the then new Cone Calorimeter.

Thus the main focus of this particular DBMS was to standardize a complete data structure for fire tests so that the data could be transmitted between laboratories and to develop a program to manage the data but not manipulate or analyse it.

Since the data structure of FDMS was created to satisfy as many of the data reporting needs of the user as possible, it would be ideal to use it as a starting point for the UCFIRE data structure.

### **2.4.1 Data Structure of FDMS**

Unlike an XML database which stores data as collections of elements under one root element and as one complete document; FDMS is a relational database where the database is organized as a collection of main data tables linked to other secondary data tables.

In FMDS 1.0 there is a main table containing the following data tests [9]:

- Cone Calorimeter (CONE).
- LIFT Apparatus (LIFT).
- Furniture Calorimeter (FURN).
- Room/Corner Test (ROOM).
- BS476-7 British Standard 476 Part 7 Surface Spread of Flame Test.
- SCHACHT for the German Brandschacht test.

- EPIRAD for the French Epiradiateur test.

Only the first four tests were retained from the FDMS 1.0 specification to the FDMS 2.0 specification [10].

This main table is then linked to a number of secondary data tables. These secondary data tables include:

- *ORGANISE* for organisations sponsoring tests, performing tests, or producing products.
- *PERSONNEL* for individuals, such as the test operator, test officer, etc.
- *PRODUCT* for product tested.
- *INSTRUM* for instrument identification.
- *CALIB* for instrument calibrations.
- *INDEX* which keeps track of what main tables have been added.

These secondary tables were then updated in the FDMS 2.0 specification to:

- *PEOPLE* for individuals, such as the test operator, test officer, etc.
- *ORGANISE* for organisations involved in the fire tests.
- *AFFLIAT* for affiliations.
- *PRODUCT* for product tested.
- *INSTRUM* for instrument identification.
- *DRVDMEAS* for FDMS base measurements.
- *DOCUMENT* stores information about documents. These may include video clips but currently FDMS 2.0 cannot play videos.
- *METHOD* for types of fire tests.
- *TEST* for details about the setup test conditions.

FDMS 2.0 also includes room for a *PRIVATE* Field that indicates whether that particular record may be viewed by a user or not [10].

Vector data is stored as separate ASCII text files (.vec), one for each fire test. Both raw and reduced data can be stored within this file so long as they have different headings.

The Reduced Vector Data format can be seen in Figure 9.

SERIAL NAME
SHORT LABEL
LONG LABEL
UNITS

**Figure 9: FDMS Reduced Vector Data Format**

The header for raw data takes the form shown in Figure 10.

CHANNEL xx
SERIAL NAME
SHORT LABEL
LONG LABEL
CALIBRATION DATA

**Figure 10: FDMS Raw Vector Data Format**

An extract from an exemplar data file can be seen below in Figure 11.

```
VECTOR DATA
VARIABLE
Time
TIME
Time from sample insertion
Seconds
0
5
10
15
20
25
30
35
40
45
50
55
60
VARIABLE
DERIVED
R.H.R.
Heat release rate
kW/m2
0
0
158.7677
174.4851
158.6999
110.9959
79.56096
80.05375
65.45976
46.74632
33.14283
23.6709
14.42107
```

**Figure 11: ASCII Serial Format for Reduced Vector Data used in FDMS**

Note that most of the field names from FDMS 1.0 were retained from FDMS 2.0 [10].

The advantage of using XML instead of the FDMS data structure is that the data would be kept together in one file rather than many different files which could be accidentally lost or corrupted. It is understandable that FDMS was not designed in this

way since the first FDMS specification was published in 1991 and the first XML specification was not published until 1996 [15].

For a more detailed description of the FDMS data structure refer to *Standardization of Formats and Presentation of Fire Data* [9] and *Data Structures for the Fire Data Management System, FDMS 2.0* [10].

## **2.4.2 FDMS Computer Program**

The FDMS computer program is chiefly concerned with managing the fire test data items. These operations include [9]:

- Accepting raw data from a given test.
- Adding a test to the database.
- Deleting a test from the database.
- Correcting erroneous data.
- Making graphs of vector data.
- Making a copy of the database.

The first item is only concerned with transforming voltage readings into useful output readings. FDMS does not include data reduction operations such as calculating gas yields, calculating the Mass Loss Rate (MLR) or the Heat of Combustion (HC) for a fire test.

A screenshot from the FDMS 1.0 application can be seen in Figure 12.

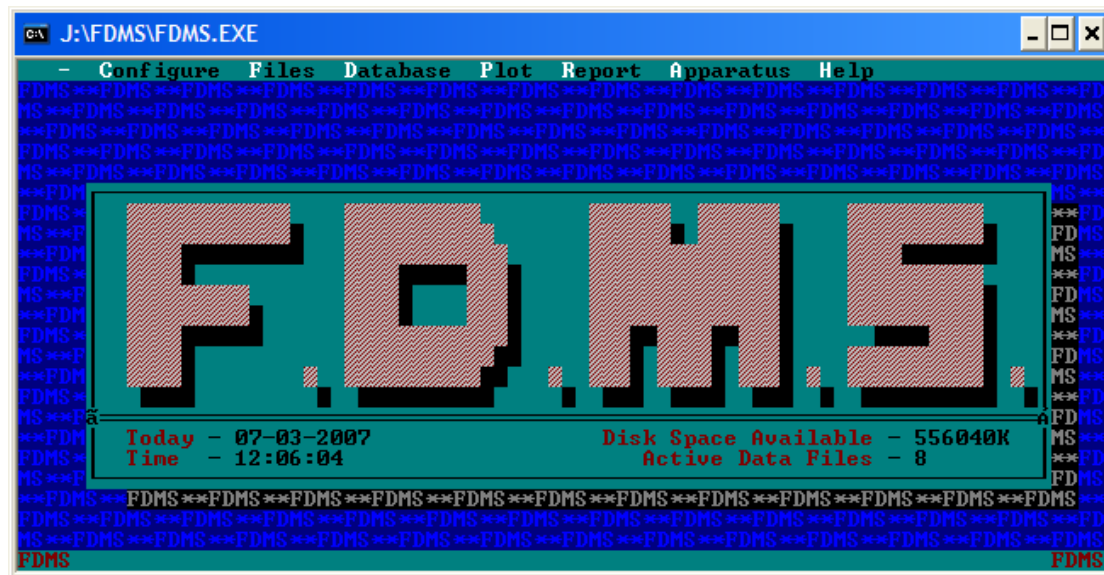


Figure 12: FDMS 1.0 Screenshot

The user interacts with this program through a series of drop down menus and uses either cursor keys or the mouse to select options.

The fields used in FDMS 2.0 [10] are shown in *Appendix A: FDMS 2.0 Derived Measurements*.

NIST provides a web interface (FASTDATA) to some of its fire tests [16] stored in the FDMS 2.0 format. No further analysis can be performed on its data.

### 2.4.3 Integration with Fire Simulation Software

While FDMS does not directly interact with external fire models the creators of this program expect that in the future fire simulation software will accept data in the FDMS format. This means that each file model would have to include routines to convert FDMS formatted data into their own propriety format which requires motivation and effort on the part of the developers of the fire simulation software.

#### **2.4.4 Limitations of FDMS 1.0 and 2.0**

Some limitations of the FDMS data structure:

- The FDMS specification requires fire models to read FDMS data instead of being able to convert it into the fire models' native format.
- The FDMS program cannot play video clips directly.
- FDMS only converts voltage readings into meaningful units; it does not perform any data reduction when importing raw data.
- FDMS does not provide tools for further analysis or reduction of the data.
- The integrity of the data stored within this database cannot be validated.
- Since the FDMS data structure consists of a number of files: the main ASCII file and its associated secondary and vector files, there is a greater chance that these files may be misplaced or corrupted.

#### **2.4.5 Advantages of FDMS**

The main advantage of FDMS is that its purpose was to be a very comprehensive database from the very start and therefore the FDMS 2.0 specification has a very comprehensive list of all the quantities that may need to be recorded in a DBMS and most of these quantities will be incorporated into the UCFIRE schema.



## 2.5 FIREBASEXML

### 2.5.1 Purpose of FIREBASEXML

Spearpoint [11] developed a fire test database (FIREBASEXML) as part of his efforts to integrate building product models with fire simulation software. Since the focus of his research was interoperability between engineering-related software tools his data structure is not as comprehensive as FDMS's data structure. FIREBASEXML only stores the Heat Release Rate (HRR) data of the burning object and some descriptive elements as shown in Figure 13.

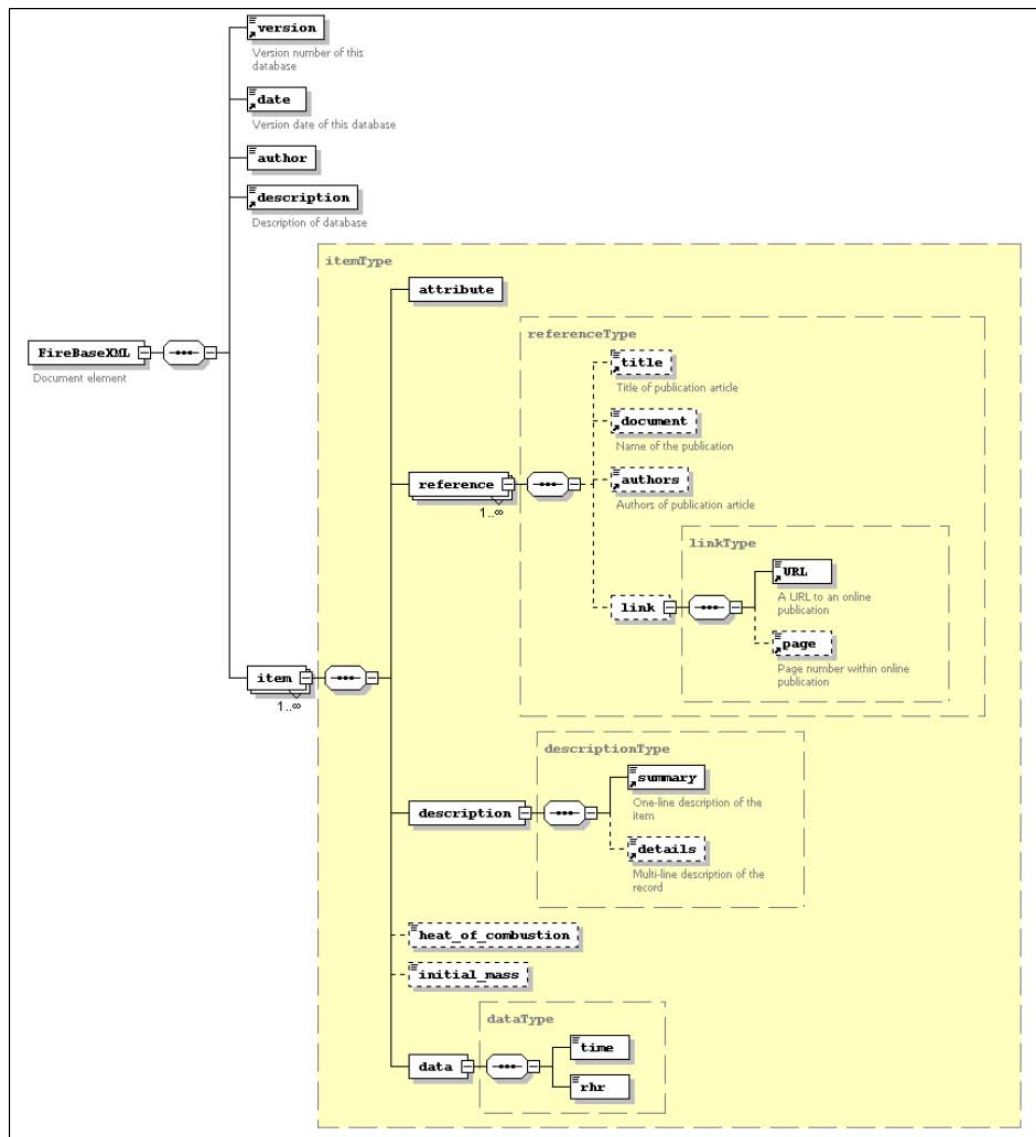


Figure 13: FIREBASEXML Data Structure

As can be seen above Spearpoint's data structure stores:

- The version number of the database.
- The version date of the database (it is unclear as to whether this refers to when the database was last modified or when it was created).
- The author of the database.
- A description of the database.
- One or more data items.

Each Data item contains:

- A description of the fire test.
- Vector data containing the HRR.
- The initial mass of the object.
- The heat of combustion for the object.
- One or more reference elements.

Each reference element contains:

- The title and name of the published document.
- The author of the document.
- A link to the document.

### **2.5.2 FIREBASEXML Computer Program**

Spearpoint also developed a User Interface (UI) called Select Fire for his fire test DBMS. He developed this application using Visual Basic 6 and then later Visual Basic.NET 2002. Screenshots of this application can be seen below in Figure 14.

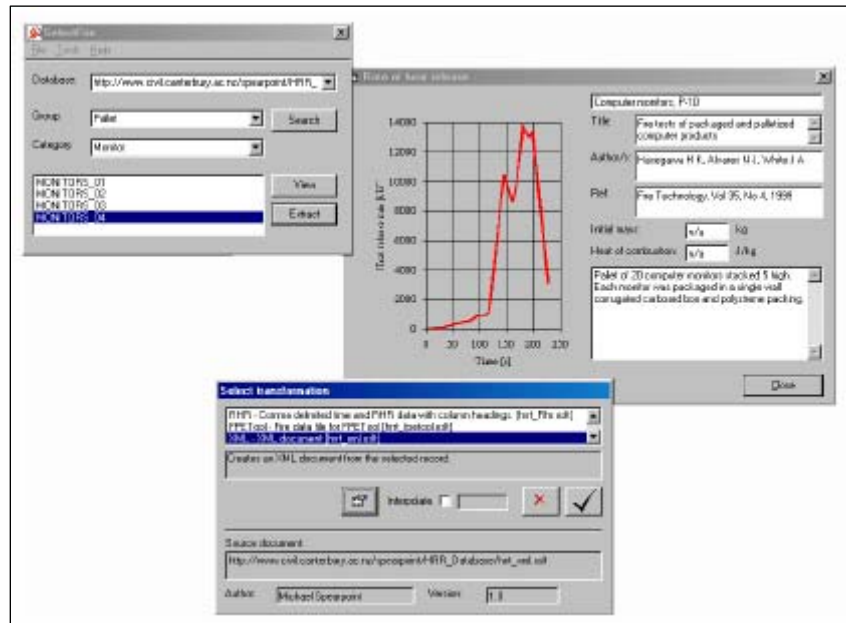


Figure 14: Select Fire Client

This program allowed a user to search for a specific fire test and be presented with the data items discussed in the last section.

### 2.5.3 Conversion of FIREBASEXML into Other Formats

As stated before, the focus of Spearpoint's research was to exchange data between different pieces of fire software. To do this Spearpoint applied a XML transformation document to the FIREBASEXML document to convert it into the desired format.

Spearpoint created a number of these transformations:

- viewDatabase.xslt and related XML transformations which converted the FIREBASEXML document into a series of web pages.
- Hrrt\_branzfire.xslt which converted the FIREBASEXML document into a form suitable for input into the BRANZFIRE zone model.

## **2.5.4 Limitations of the FIREBASEXML Data Structure**

Some limitations of the FIREBASEXML data structure:

- Currently this XML schema makes extensive use of attributes to store data instead of elements but there is some debate over whether this is the best method. Some people argue that attributes should never be used at all – the information would be better contained within a new child element [17].
- FIREBASEXML can only store a limited range of information about the fire tests. This was because Spearpoint's focus was not to create a comprehensive data structure but a limited one that could be used in testing data exchange algorithms between different fire product models.

## **2.5.5 Advantages of the FIREBASEXML Data Structure**

- Spearpoint's FIREBASEXML data structure can be easily extended to store a complete set of fire test data.
- Transformations may be easily applied to the FIREBASEXML data structure. A single transformation document may be applied to the FIREBASEXML structure to convert it to a form suitable for BRANZFIRE or CFAST. FDMS however relied on the fact that the fire simulation software would adopt its format.
- The integrity of data stored in the XML format can be easily validated by a validating parser.
- FIREBASEXML stores all of the database's data in a single coherent document.

## **2.6 Summary**

Since no other publicly available existing fire test database automatically reduces raw fire test data and stores it within a DBMS; the purpose of the proposed UCFIRE DBMS is to provide a method of automatically reducing, where needed, fire test data in a mechanistic fashion and storing the data in a logical and complete fashion.

All the other fire tests DBMS lack facilities to further analyse fire tests or groups of fire tests; so the UCFIRE DBMS is designed to allow for the analysis of individual data items and groups of data items.

The FIREBASEXML data structure provides a clear and very extensible data structure with the inherit abilities of XML documents to be validated by a validating parser, or completely transformed into a format suitable for external fire simulation software. Thus FIREBASEXML will form the basis of the new fire test DBMS: UCFIRE.

Since the goal of UCFIRE is to allow for further analysis of its data including the use of subsets of its stored data to be used in fire simulation software; it is not concerned with storing raw data items like calibration constants.

UCFIRE is designed to be as extensible as possible to allow for the incorporation of new fire tests but for now the following fire tests will be stored within UCFIRE:

- Cone Calorimeter.
- Furniture Calorimeter.
- Room/Corner test.
- LIFT tests.
- Ignitability Apparatus tests.

The first four are covered by the FDMS 2.0 specification and the last was included at the author's discretion.

Since FDMS's goal was to incorporate as many data fields as possible; it would be an ideal starting point for the list of quantities that should be stored in the UCFIRE DBMS.

The scope of all the different type of data fields required for each fire test performed is best found by examining the standard test report requirements, even though UCFIRE will allow a subset of these requirements to be recorded if a standard test was not performed.

### 3 Standard Fire Test Report Requirements

This chapter will inspect data storage requirements of the relevant standards for the following fire tests:

- Cone Calorimeter.
- Furniture Calorimeter.
- Room/Corner Test.
- LIFT Apparatus Test.
- Ignitability Apparatus Test.

#### 3.1 Cone Calorimeter

##### 3.1.1 Cone Calorimeter Test Description

The Cone Calorimeter is a bench scale tool first described in a report in 1982 and is used primarily to determine the heat release rate of a burning object based on oxygen consumption calorimeter [18]. The layout of the Cone Calorimeter can be seen in Figure 15.

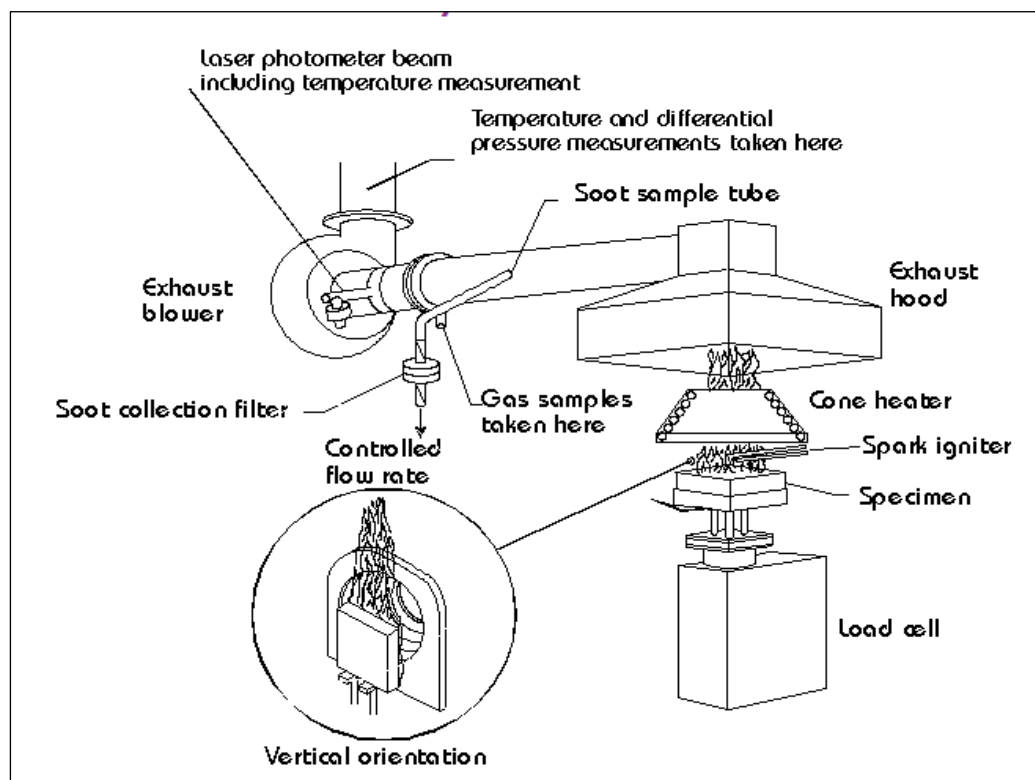


Figure 15: Cone Calorimeter Layout [18]

The specimen is exposed to a constant heat flux created by an electric conical heater element, if the incident heading flux exceeds the minimum flux for ignition ( $\dot{q}_{ig,min}''$ ) for the sample the specimen will ignite and the decrease in the amount of available oxygen is measured inside the exhaust duct.

Since for most materials approximately 13.1 MJ/kg of heat is released per 1 kg of oxygen consumed [19]; the heat release rate can be found with Equation 3.1.

$$\dot{Q}(t) = \left( \frac{\Delta h_c}{r_0} \right) \left( 1.10 \kappa \sqrt{\frac{\Delta P}{T_e}} \right) \frac{(X_{O_2(t)}^0 - X_{O_2(t)})}{1.105 - 1.5 X_{O_2(t)}} \quad (3.1)$$

Where

$\dot{Q}(t)$  = The heat release rate (kW).

$$\left( \frac{\Delta h_c}{r_0} \right) = 13.1 \text{ MJ / kg} \quad (3.2)$$

$\Delta h_c$  = The net heat of combustion (kJ/kg).

$r_0$  = Stoichiometric oxygen/fuel ratio (-).

$\kappa$  = The calibration constant for oxygen consumption analysis ( $\text{m}^{0.5} \text{kg}^{0.5} \text{K}^{0.5}$ ).

$\Delta P$  = The orifice meter pressure differential (Pa).

$T_e$  = The absolute temperature of the gas at the orifice meter (K).

$X_{O_2(t)}$  = Mole fraction of oxygen in the exhaust duct before delay time correction (-).

$X_{O_2(t)}^0$  = Mole fraction of oxygen in the analyser (-).

### 3.1.2 Standard Requirements

The Cone Calorimeter standard used to develop the UCFIRE schema was *ASTM E 1354 – 02: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter* [19].

The standard's experimental thesis requires the following data to be stored for each Cone Calorimeter test:

1. Specimen identification code or number.
2. Manufacturer or submitter.



3. Date of test.
4. Operator.
5. Composition or generic identification.
6. Specimen thickness.
7. Specimen mass.
8. Colour of specimen.
9. Details of specimen preparation by the testing laboratory.
10. Test orientation, specimen mounting, and whether the retainer frame, the wire grid, or other special mounting procedures were used.
11. Heating flux and exhaust system flow rate.
12. Number of replicate specimens tested under the same conditions.
13. Time to sustained flaming.
14. Heat release rate (per unit area) curve ( $\text{kW/m}^2$ ).
15. Peak  $\dot{q}''$  and average  $\dot{q}''$  values for the first 60, 180, and 300 s after ignition or for other appropriate periods ( $\text{kW/m}^2$ ). If sustained flaming does not occur an appropriate period would begin with the next reading after the last negative value of the heat release rate reading at the beginning of the test.
16. Total heat released by the specimen ( $\text{MJ/m}^2$ ).
17. Average  $\Delta h_{c,eff}$  for the entire test ( $\text{MJ/kg}$ ).
18. Curve of  $\Delta h_{c,eff}$  ( $\text{MJ/kg}$ ).
19. Mass remaining after test.
20. Sample mass loss rate ( $\text{kg/m}^2$ ). The average specimen mass loss rate ( $\text{g/m}^2\text{s}$ ) computed over the period, starting when 10 % of the ultimate specimen mass loss occurred and ending when 90 % of the ultimate specimen mass loss occurred.
21. Smoke obscuration and the average specific extinction area ( $\text{m}^2/\text{kg}$ )
22. Values determined in 13, 15, 17 and 21 averaged for all specimens.
23. Additional observations (including times of transitory flaming or flashing) if any.
24. Difficulties encountered in testing, if any.

Other Test Report requirements include:

25. Plot of heat release rate versus time.
26. Plot of rate of smoke release versus time.
27. Plot of optical density versus time.
28. Plot of mass loss versus time.
29. Plot of concentration of carbon monoxide versus time.
30. Plot of concentration of carbon dioxide versus time.
31. Plots of concentration of any other measured combustion gas versus time
32. Plot of duct temperature versus time.
33. Report smoke obscuration, Carbon monoxide and temperature measurements  
in the room in the same fashion if they have been made.
34. Photographs or videotape of the fire development.

Observations for the Test Report must include:

35. Ignition of the specimen.
36. Position of the flame front.
37. Melting and dripping.
38. Occurrence of the pool fire under the specimen.
39. General description of the burning behaviour, and
40. Any other event of interest.

## 3.2 Furniture Calorimeter

### 3.2.1 Furniture Calorimeter Test Description

The bench scale cone calorimeter test can measure the properties of individual materials but is not large enough to conduct, say, a furniture fire test. The large scale equivalent of the Cone Calorimeter is the Furniture Calorimeter (Figure 16). The specimen is ignited by a specified ignition source and then burns under well ventilated conditions.

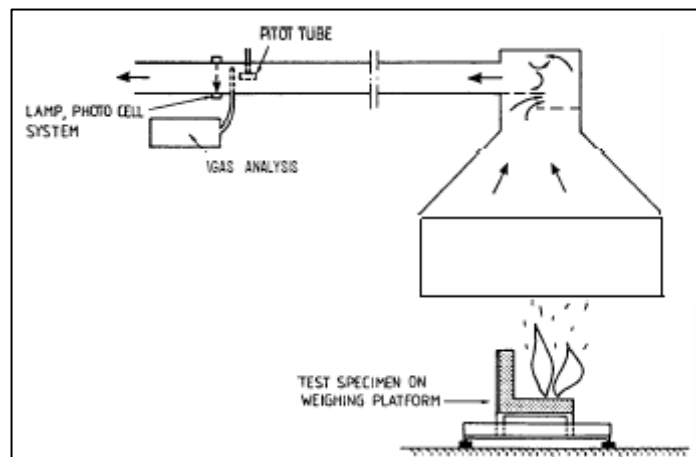


Figure 16: Furniture Calorimeter Test Configuration [20]

### 3.2.2 Standard Requirements

The Furniture Calorimeter standard used to develop the UCFIRE schema was *NT Fire 032: Nordtest Method* [20].

The standard's experimental report requires the following data to be stored for each test:

1. Name and address of the testing laboratory.
2. Date and identification number of the report.
3. Name and address of the client
4. Purpose of the test.
5. Method of sampling.
6. Name of manufacturer or supplier of the product.
7. Name or other identification marks and description of the product.

8. Density or weight per square unit and thickness of the main components in the product.
9. Description of the specimens.
10. Conditioning of the specimens.
11. Date of test.
12. Test method.
13. Time - mass burning rate.
14. Time - total rate of heat release.
15. Time - production rate of carbon monoxide.
16. Time - production rate of carbon dioxide.
17. Time - production rate of light obstructing smoke.
18. Time – mass flow in the exhaust duct.
19. Description of the fire development (photographs).
20. Calibration results according to paragraph 9.2 of the standard.
21. Effective heat of combustion determined from the quotient between the measured rate of heat release and the mass burning rate (optional).
22. The production rates given in 15 and 17 normalized versus measured rate of heat release and measured mass burning rate (optional).
23. When appropriate: designation of the product according to criteria expressed in official standards or regulations (optional).
24. Deviations from the test method, if any (optional).
25. When not identified in the test method, equipment and instruments used (optional).

### 3.3 Room/Corner Test

#### 3.3.1 Room/Corner Test Description

The room/corner test simulates a room size fire that starts in a corner of small room with a single open doorway. This experimental setup can be seen in Figure 17.

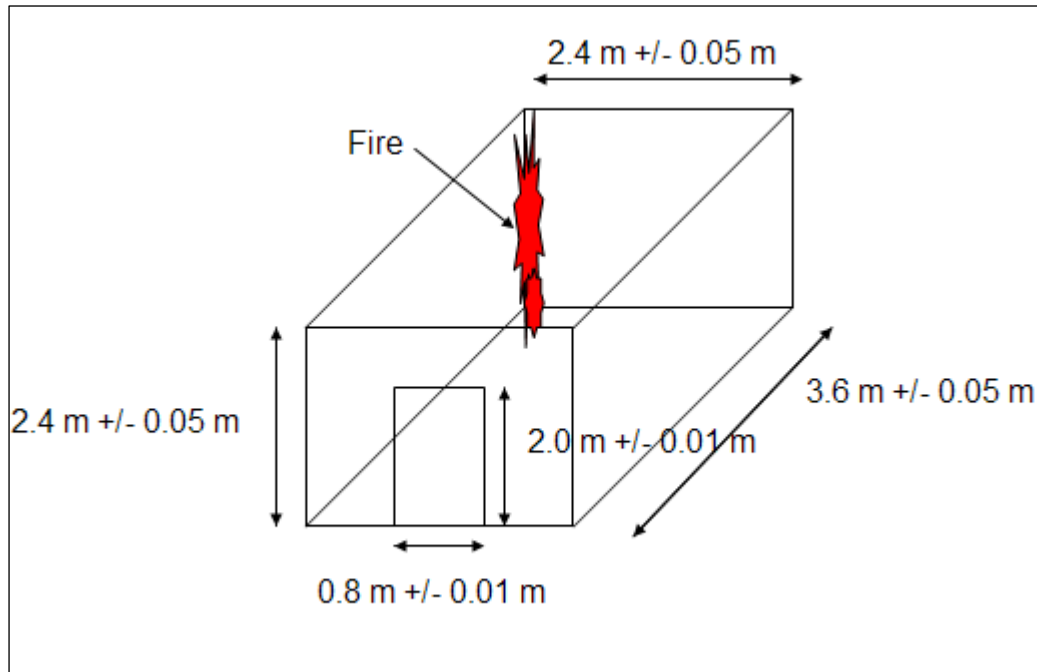


Figure 17: Room/Corner Test Setup

#### 3.3.2 Standard Requirements

The Room/Corner Test standard used to develop the UCFIRE schema was *ISO 9705:1993(E): Full-scale room test for surface products* [21].

The standard's experimental report requires the following data to be stored for each test:

1. Name and address of the testing laboratory.
2. Date and identification number of the report.
3. Name and address of the client.
4. Purpose of the test.
5. Method of sampling.

6. Name of manufacturer or supplier of the product.
7. Name or other identification marks and description of the products.
8. Density or mass per square meter and description of the products.
9. Date of supply of the product.
10. Description of the specimens and mounting technique.
11. Conditioning of the specimens.
12. Date of the test.
13. Test method.
14. Time/heat flux incident on the meter at the centre of the floor.
15. Time/volume flow in the exhaust duct.
16. Time/rate of heat release; and if burner is included, time/heat release from the burner.
17. Time/production of carbon monoxide at reference temperature and pressure.
18. Time/production of carbon dioxide at reference temperature and pressure.
19. Time/production of light-obscuring smoke at actual duct flow temperature.
20. Description of the fire development (photographs).
21. Calibration results involving the time to reach within 10 % of a given series of step changes in the HRR shown in Table 1.
22. Time/surface temperature of the product.
23. Time/vertical temperature profile in the doorway.
24. Time/mass flow through the doorway.
25. Time/convective heat flow through the doorway.
26. Time/production of Hydrocarbons ( $\text{CH}_n$ ) at a reference temperature and pressure.
27. Time/production of Nitrogen Oxides ( $\text{NO}_x$ ) at a reference temperature and pressure.
28. Time/production of Hydrogen Cyanide (HCN) at a reference temperature and pressure.
29. Designation of the product according to criteria expressed in official standards or regulations.

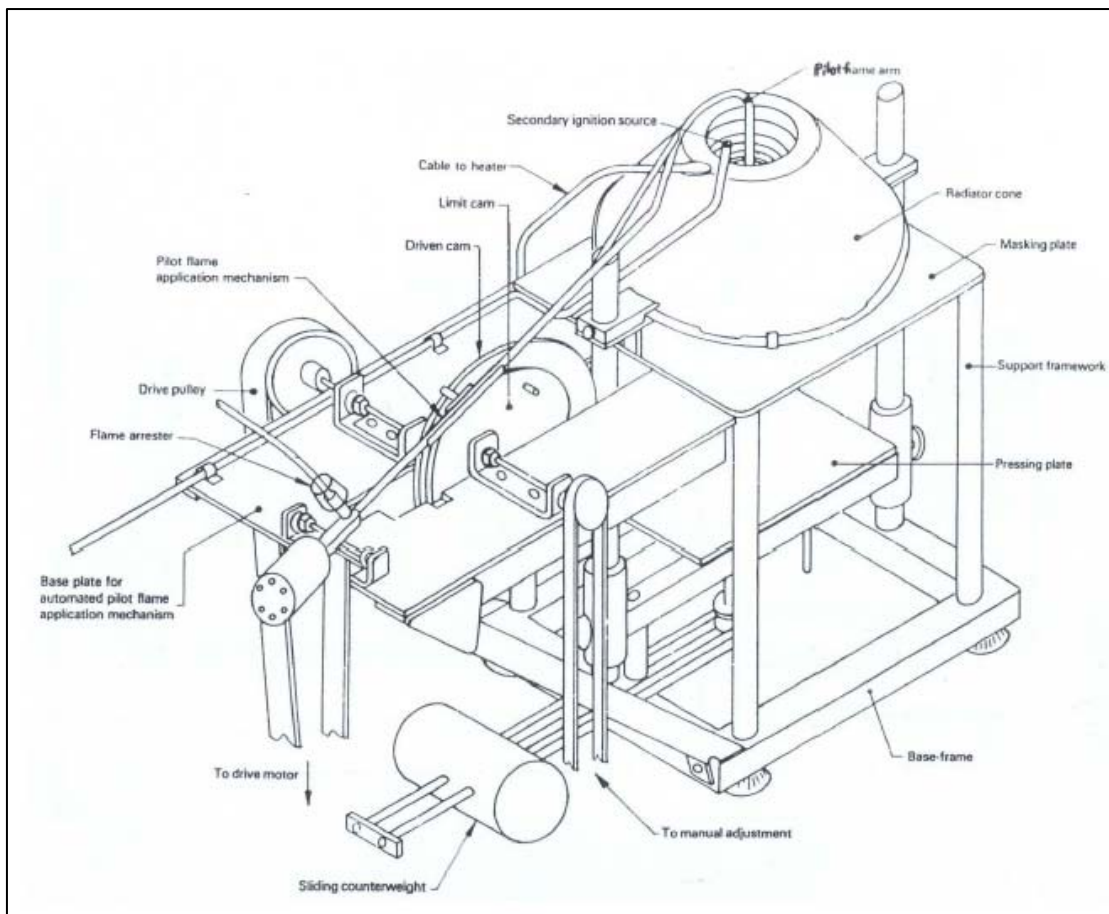
<b>Time (min)</b>	<b>Burner Heat Output (kW)</b>
0 to 2	0
2 to 7	100
7 to 12	300
12 to 17	100
17 to 19	0

**Table 1: Burner HRR Step Changes**

### 3.4 ISO Ignitability Test

#### 3.4.1 ISO Ignitability Test Description

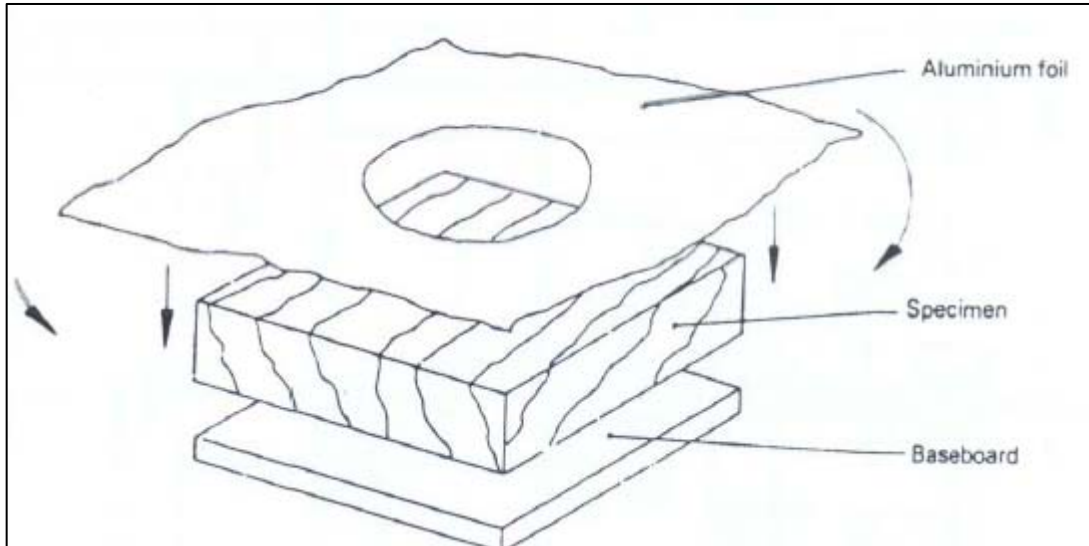
The ISO ignitability test involves exposing the specimen to a series of heat fluxes, up to  $50 \text{ kW/m}^2$ , and recording the time to ignition. A schematic diagram of the ISO ignitability apparatus can be seen in Figure 18.



**Figure 18: ISO Ignitability Apparatus [22]**

The test material is composed of a baseboard to prevent heat loss and an aluminium foil covering the specimen itself. As required by *BS476:Part13:1987* [23] the baseboard must have sides measuring 165 mm by 165 mm or 5 mm below this value. The oven dried density of the board must be  $825 \pm 125 \text{ kg/m}^3$  with a thickness of 6mm. This is to ensure zero heat loss from the back of the specimen allowing the semi-infinite assumption for thermally-thick materials. This can be seen in Figure 19.





**Figure 19: Specimen Composition [22]**

The critical heat flux and other relevant thermal properties of the material are found by applying one of two correlations produced by Mikkola and Wichman [24].

### **Thermally-Thin Solids:**

Thermally-thin solids are those that experience non negligible heat gradients, and experience heat loss out the back of the solid. Assuming that the convective heat loss is negligible to the radiative heat loss the time to ignition can be approximately with Equation 3.3.

$$t_{ig} = \rho L_o c \frac{(T_{ig} - T_{\infty})}{(\dot{q}_e'' - \dot{q}_{crit}'')} \quad (3.3)$$

Where

- $t_{ig}$  = The time to ignition (s).
- $T_{ig}$  = The ignition temperature (K).
- $T_{\infty}$  = The ambient temperature (K).
- $\rho$  = The density of the specimen (kg/m<sup>3</sup>).
- $L_o$  = The thickness of the material (m).
- $c$  = The specific heat of the material (J/kg/K).

Equation 3.3 is used by fitting a straight line to the inverse time to ignition ( $1/t_{ig}$ ) versus heat flux  $\dot{q}_e''$  [24]. The x-intercept yields the critical flux: essentially the point where the time to ignition is zero. It is the critical flux, not the minimum flux, as it is found by correlation rather than experimentally.

### **Thermally-Thick Solids:**

Thermally-thick solids are those that experience negligible heat gradients, and experience no heat loss out the back of the solid. The time to ignition [24] can be found with Equation 3.4.

$$t_{ig} = \frac{\pi}{4} \rho L_o c \frac{(T_{ig} - T_{\infty})^2}{(\dot{q}_e'' - \dot{q}_{crit}'')^2} \quad (3.4)$$

Equation 3.4 is used by fitting a straight line to the inverse square root of time ignition ( $1/\sqrt{t_{ig}}$ ) versus heat flux  $\dot{q}_e''$  [24]. The x-intercept yields the critical flux.

### **3.4.2 Standard Requirements**

The ISO Ignitability Test standard used to develop the UCFIRE schema was the ISO Ignitability Test according to the description of *BS476: Part 13:1987: Fire Test on building materials and structures* [23].

The standard's experimental report requires the following data to be stored for each test:

1. The specimen ignition times for each irradiance tested.
2. Any observations made during the test and comments on any difficulties experienced during the tests.
3. Name and address of the test laboratory.
4. Name and address of the test sponsor.
5. Name and address of the manufacturer/supplier.
6. Full description of the product tested including trade name, together with its composition, construction, orientation, thickness, density and mass of

the conditioned specimen before the test and, where appropriate, the face subjected to the test.

7. Details of substrates used and fixing methods shall be given.
8. With composites and assemblies the thickness and density of each component will be given, together with the apparent (i.e. overall density of the whole).
9. For some products the date of manufacture and information about subsequent treatment and/or exposure may be of importance.
10. The statement: *“The test results relate only to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the products in use.”*

### 3.5 LIFT Apparatus Test

#### 3.5.1 LIFT Test Description

The Lateral Ignition and Flame Spread (LIFT) test is concerned with determining the material properties of a vertically orientated specimen in response to two separate tests:

- An ignition test: where the specimen is exposed to a uniform and constant heat flux. The time to ignition at different heat fluxes is recorded.
- A lateral flame spread test: where the specimen is exposed to a laterally varying applied radiant flux.

The experimentally set can be seen in Figure 20: LIFT Experimental Setup [25].

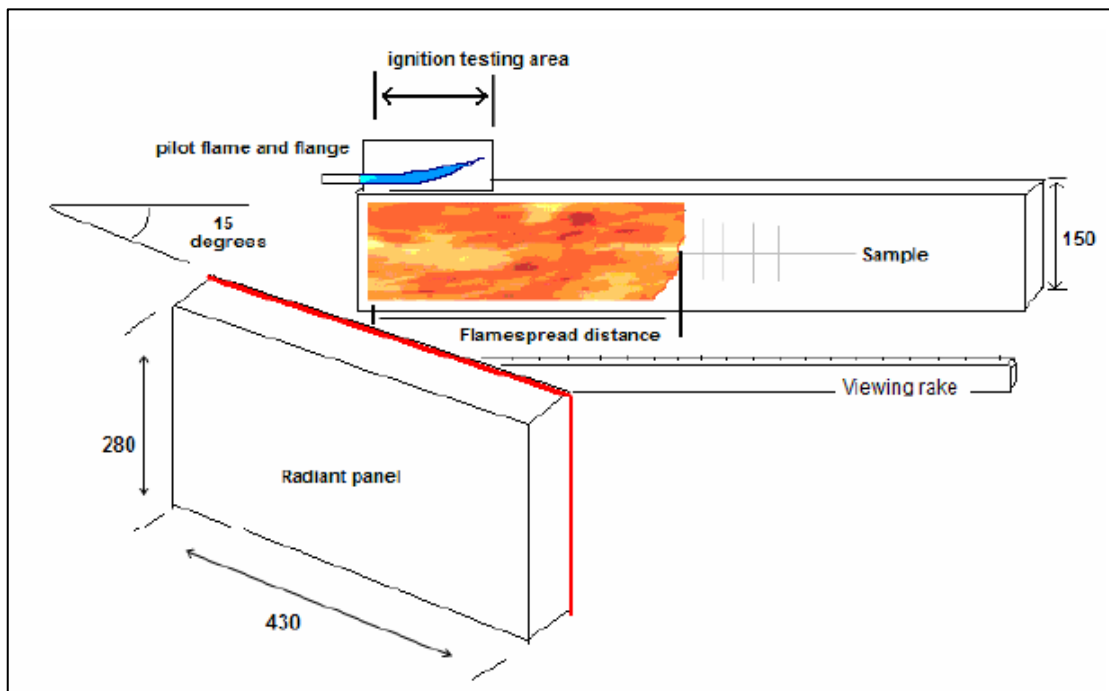


Figure 20: LIFT Experimental Setup [25]

The radiant panel is powered by gas and aligned at a 15 degree angle to the specimen. An approximate radiative heat profile can be seen in Figure 21.

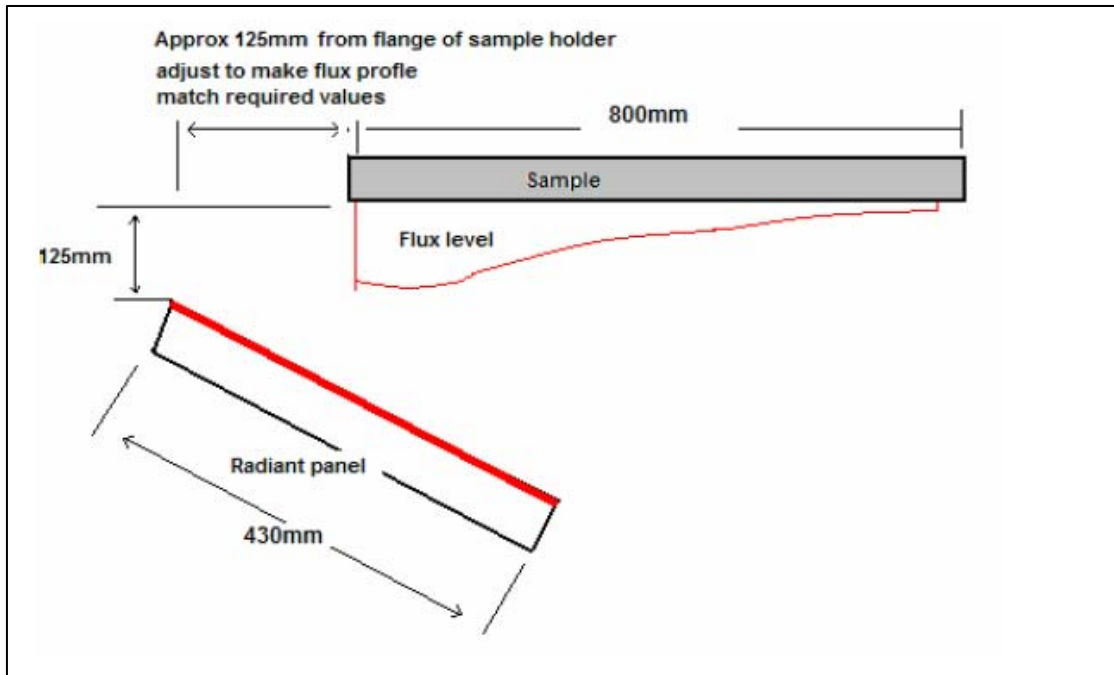


Figure 21: Flux Profile Along the Specimen [25]

The required flux profile, or  $F(x)$  can be seen below in Figure 22.

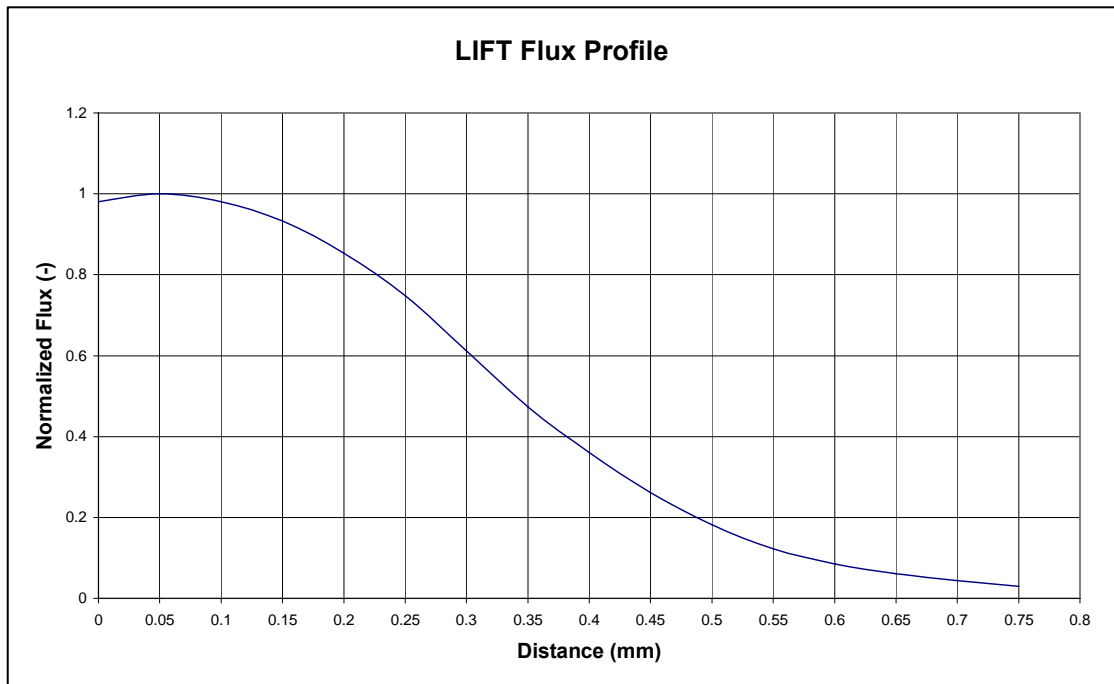


Figure 22: Flux Profile as Specified by ASTM E 1321-97a [26]

### Ignition Test:

The ignition test involves subjecting the specimen to a heating flux of  $30 \text{ kW/m}^2$  at the  $0.05 \text{ m}$  position of the lateral ignition apparatus and decreasing this flux in  $5 \text{ kW/m}^2$  increments until ignition does not occur. The flux is then increased in  $2 \text{ kW/m}^2$  increments until ignition occurs [26]. A plot of this flux-time data would have the general shape shown below in Figure 23.

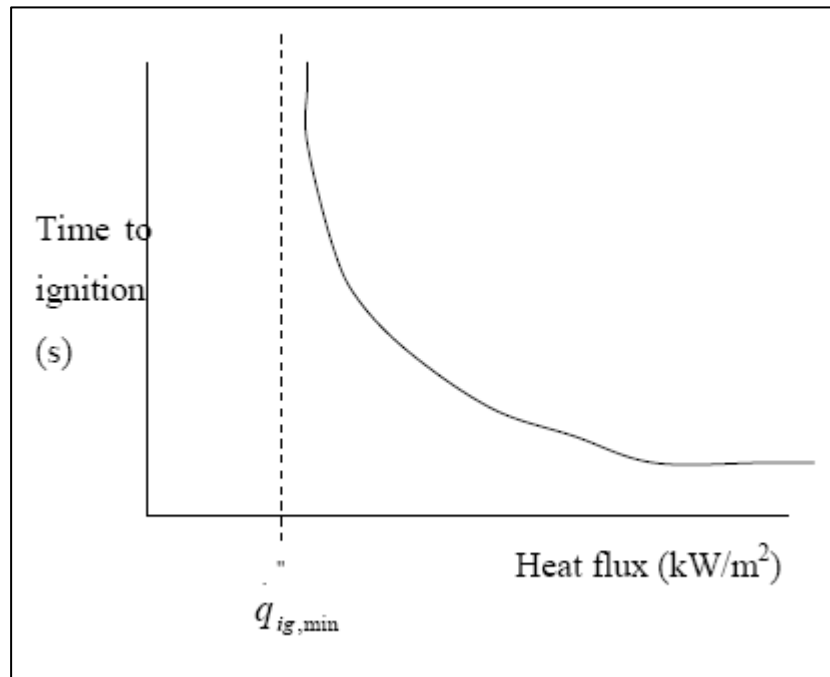


Figure 23: Ignition Test Data [25]

The asymptote in the figure indicates the minimum flux ( $q''_{ig,min}$ ) to the surface of the specimen that could be expected to produce ignition. The critical flux ( $q''_{crit}$ ) is similar to this minimum flux except it is found by the use of a correlation. This correlation involves fitting a straight line to the ignition flux against  $(1/\sqrt{t_{ig}})$ . The general shape of this correlation can be seen in Figure 24.

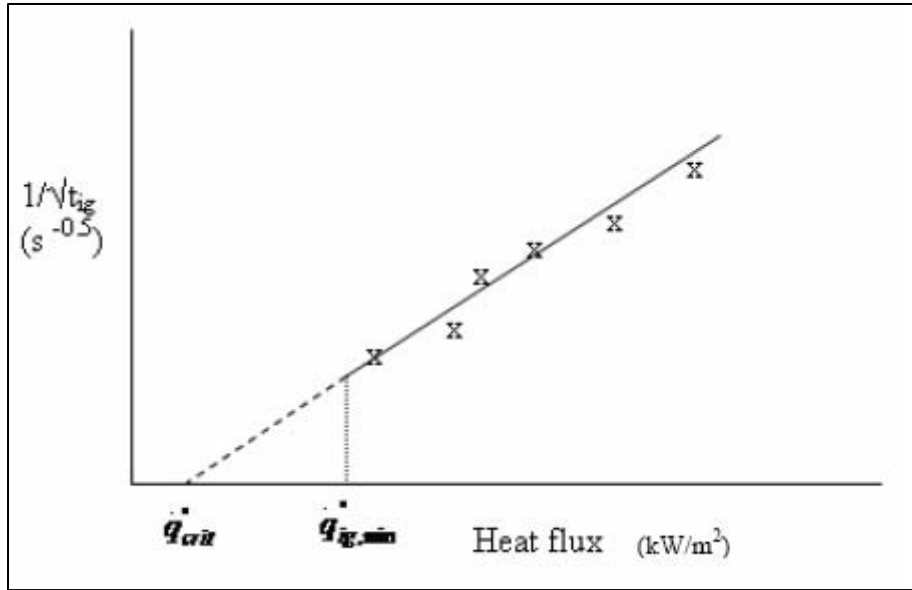


Figure 24: Critical Flux Correlation [25]

By plotting  $\dot{q}_{ig,min}'' / \dot{q}_e''$  versus  $\sqrt{t_{ig}}$  and fitting a straight line to this data set it is possible to determine the ignition parameters  $b$  and  $t^*$ . The important characteristics of this correlation can be seen in Figure 25.

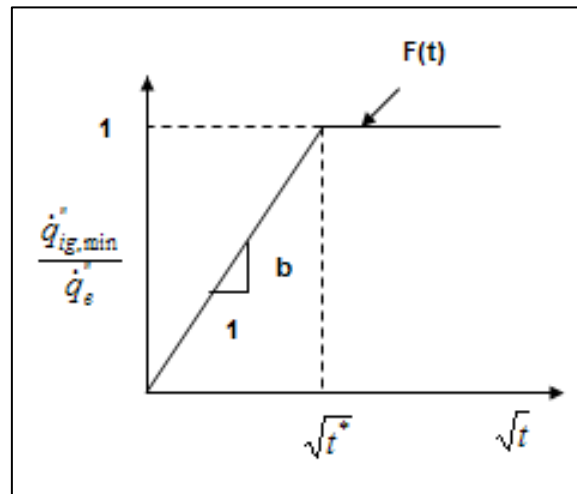


Figure 25: LIFT Ignition Flux Correlation

Where

$$F(t) = \begin{cases} b\sqrt{t}, & t \leq t^* \\ 1, & t > t^* \end{cases} \quad (3.5)$$

$b$  = Ignition correlation parameter ( $s^{-0.5}$ ).

$t^*$  = Characteristic equilibrium time (s).

The characteristic equilibrium time is the amount of time that the specimen must preheat before the pilot flame is used to ignite the specimen for the flame spread portion of the LIFT test.

The characteristic equilibrium time is found with the following expression (Equation 3.6).

$$t^* = \left( \frac{1}{b^2} \right) \quad (3.6)$$

Equation 3.5 was found by correlating a number of experimental tests [26]. It is the experimental counterpart to Equation 3.7.

$$T_s - T_\infty = \frac{\dot{q}_e''}{h} \left( 1 - \exp(-\tau) \operatorname{erfc}(\sqrt{\tau}) \right) \quad (3.7)$$

Where

$T_s$  = The surface temperature of the semi infinite solid (K).

$T_\infty$  = The ambient temperature (K).

$h$  = The heat loss coefficient (kW/m<sup>2</sup>K).

$t$  = Time (s).

$k\rho c$  = The thermal heating property ((kW/m<sup>2</sup>K)<sup>2</sup>s).

$$\tau = \frac{h^2 t}{k\rho c} \quad (3.8)$$

The semi-infinite/thermally-thick assumption required by the test standard assumes that one dimension of the solid effectively appears infinite to the conductive transfer of heat i.e. no heat loss occurs out the back of the solid. This assumption is satisfied experimentally by the inclusion of an insulation backing board for the specimen. For the LIFT test this backing board is 25 +/-5 mm thick with a density of 200 +/- 100 kg/m<sup>3</sup>. The theory of ignition used in the LIFT tests also assumes that the  $k\rho c$  for most organic solids falls in the range of 0 to 10<sup>-7</sup> m<sup>2</sup>/s so their depth of heating for piloted ignition is 2 to 5mm [26]. Since the specimen thickness is typically 20 mm or



more; then negligible heat gradients occur across the specimen and negligible heat loss occurs out the back of the specimen.

### Flame Spread Test:

The specimen is placed into the apparatus and allowed to preheat for the specified time ( $t^*$ ). The pilot flame is then applied to the specimen to ignite the pyrolysis products. The lateral progression of the flame as a function of time and distance is then recorded.

A three point moving average is applied to the flame velocity using Equation 3.9.

$$V = \frac{\sum tx - \frac{\sum t \sum x}{3}}{\sum t^2 - \frac{(\sum t)^2}{3}} \quad (3.9)$$

Plotting the linear section of  $V^{-0.5}$  versus  $\dot{q}_e''(x) F(t)$  yields Figure 26.

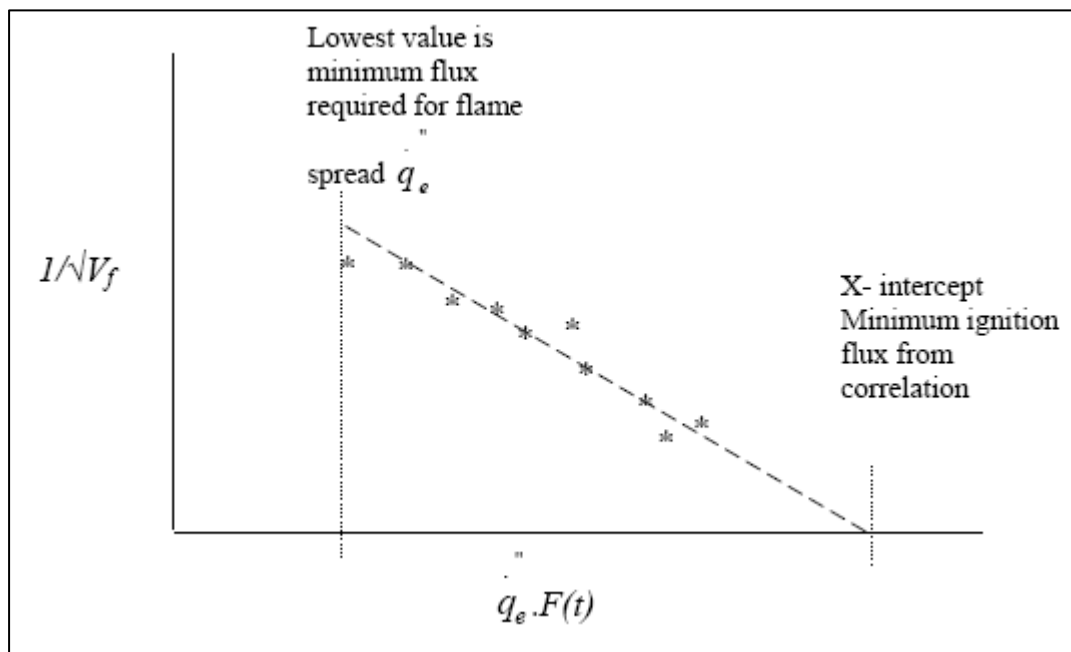


Figure 26: LIFT Flame Spread Correlation [25]

Note  $\dot{q}_e''(x)$  can be found from Equation 3.10:

$$\dot{q}_{e(x)}'' = F(x)\dot{q}_{e(50mm)}'' \quad (3.10)$$

Where

$$\dot{q}_{e(50mm)}'' = \text{The flux at 50 mm (kW/m}^2\text{)}.$$

The x-intercept gives another estimate of the minimum ignition flux (by correlation).

The lowest value of  $\dot{q}_{e(x)}'' F(t)$  is the minimum flux required for flame spread.

The LIFT standard assumes that ignition occurs when the surface temperature of the solid reaches a critical value. Performing an energy balance on the surface of the material yields Equation 3.11.

$$\dot{q}_{ig}'' = h_c (T_{ig} - T_\infty) + \sigma (T_{ig}^4 - T_\infty^4) \quad (3.11)$$

Where

$$\dot{q}_{ig}'' = \text{The heating flux (kW/m}^2\text{)}.$$

$$h_c = \text{The convection coefficient (15 W/m}^2\text{) [26].}$$

$$T_{ig} = \text{The temperature of the surface of the material at ignition (K).}$$

$$T_\infty = \text{The ambient temperature (K).}$$

$$\sigma = \text{The Stefan-Boltzman constant } (\sigma = 5.670 \times 10^{-8} \text{ W / m}^2 \text{ K}) \text{ [27].}$$

Once the minimum flux for ignition and flame spread has been determined, Equation 3.11 can be solved iteratively, as explained in a later chapter of this thesis, to determine the minimum temperature for ignition and flame spread.

### 3.5.2 Standard Requirements

The LIFT Test standard used to develop the UCFIRE schema was *ASTM E 1321-97a Standard Test Method for Determining Material Ignition and Flame Spread Properties* [26].

The standard's experimental report requires the following data to be stored for each test:

1. The date.
2. Observations made on each specimen.
3. Name and address of the testing laboratory.
4. Identification of the specimen including manufacturer and code designation, thickness, density and the composition of the material where known.
5. Identification of the specimen backing material including thickness, density, and thermal conductivity where known.
6. A table or graph, or both, showing ignition times for external fluxes.
7.  $\dot{q}_{ig,min}''$ , the minimum flux necessary for ignition ( $\text{kW/m}^2$ ).
8.  $T_{ig,min}$ , the minimum surface temperature necessary for ignition (K).
9.  $b$ , the Ignition correlation parameter ( $\text{s}^{-0.5}$ ).
10.  $t^*$ , time for specimen to reach thermal equilibrium (s).
11.  $k\rho c$ , the Thermal heating property ( $(\text{kW/m}^2\text{K})^2\text{s}$ ).
12. Surface flux at the 50 mm position ( $\text{kW/m}^2$ ).
13. Flame front arrival time (s) at 25 mm increments along the specimen surface .
14.  $C$ , the Flame heat transfer parameter ( $\text{m}^{s/2}/\text{kWs}^{0.5}$ ).
15.  $\dot{q}_{s,min}''$ , the minimum flux necessary for flame spread (K).
16.  $T_{s,min}$ , the minimum temperature necessary for flame spread (K).
17.  $\Phi$ , the Flame heating parameter ( $(\text{kW})^2/\text{m}^3$ ).

### **3.6 Summary**

This chapter investigated the reporting requirements of five standard fire tests. The reporting requirements for the Cone Calorimeter, Furniture Calorimeter, and Room/Corner tests were quite dissimilar to the reporting requirements of the LIFT and Ignitability Apparatus tests. The Cone Calorimeter, Furniture Calorimeter, Standard Test Method for Fire Testing of Upholstered Furniture, and Room/Corner tests stored primarily time series data while the LIFT and Ignitability Apparatus tests stored primarily other series data; that is vectors which are not a function of time.

The challenge of creating the UCFIRE data structure is to make a data structure comprehensive enough to store all of the quantities required by each individual fire test but to do so in a way so that any discrepancies in the reporting requirements do not conflict with each other. Also it is important to remember that the data should be stored in a way that is easily extracted using Visual Basic.NET.

Perhaps it is not possible for all of these requirements to be satisfied by one document (XML Schema) without a substantial increase in the complexity of the document or program and some minor compromises may need to be made to accommodate all the data types without producing an unwieldy and complex data structure specification. The creation of the UCFIRE data structure will be discussed in depth in the next chapter of this thesis.

## **4 Creation of the UCFIRE Data Structure**

### **4.1 UCFIRE Schema**

Chapter 2 of this thesis examined the advantages and disadvantages of data structures used in publicly available fire test DBMS. The FDMS 2.0 specification contains a very comprehensive list of all the data elements that need to be stored from fire tests, but it does not allow for the automation of the data reduction process or for the further manipulation of its stored data. However this is an excellent starting point for all the fields that need to be stored within the new UCFIRE DBMS.

The data structure of UCFIRE should then be verified against the reporting requirements of the standard fire tests discussed in the Chapter 3 of this thesis. It may not be possible to satisfy all of these reporting requirements in one document without making either the document specification, raw Excel spreadsheet (to be discussed later in Chapter 6 of this thesis) or User Interface (UI) too unwieldy or unnecessarily complex, since these standards require many different reporting requirements. For non-standard fire tests a subset of the standard reporting requirements should also be considered valid by the validating XML parser.

The fire simulation software's databases represent a subset of all the information that could be stored in a fire test DBMS. These models all have their own propriety format and FDMS requires that these models recognise the FDMS 2.0 specification. This would suggest that XML would be ideal to describe the data structure of the new UCFIRE DBMS as a single XSLT transformation file could be applied to the UCFIRE DBMS to convert it into a specific format for use with any one of the fire simulation software packages. Also XML stores all its data in a single coherent document, and unlike FDMS, its data integrity can be easily verified by a validating parser. Spearpoint [11] created a fire test DBMS using the advantages of XML as part of his efforts to integrate building product models with fire simulation software. This data structure is not as comprehensive as the FDMS specification but it is clear and easily extensible and will form the basis of the new data structure UCFIRE.

Thus the UCFIRE specification will be based on the extensible XML data structure created by Spearpoint [11] and it will have many of the derived measurements mentioned in the FDMS 2.0 specification [10]. This data structure should also contain all of the data fields required by the reporting requirements of the standard fire tests discussed in Chapter 4 of this thesis.

#### 4.1.1 Root Element

The *FIREBASEXML* schema begins with the *FIREBASEXML* root element and has *version*, *date*, *author*, *description* and *item* child elements. This root element was renamed *UCFIRE* and all the child elements were essentially copied over from *FIREBASEXML* schema into the new *UCFIRE* schema. The *date* element however was split into two separate elements: date *Created* and date *LastModified*. The latter will be used when checking to see if a web connection to a UCFIRE document stored on a web server is still valid. The *item* element was pushed one level down below a new element called *Items*. Thus each new fire test will be stored in a new *Item* element under the *Items* element. This new data structure can be seen in Figure 27.

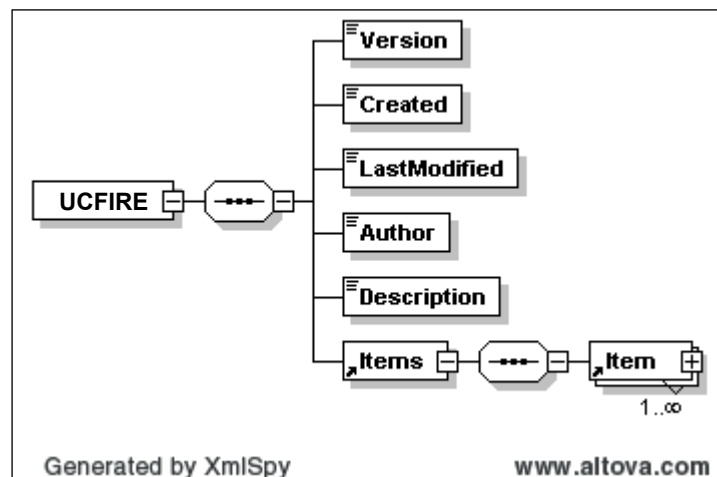


Figure 27: UCFIRE DBMS's Root Element

Note that, unlike the *FIREBASEXML* structure, a UCFIRE document is only valid if one or more fire tests are stored inside rather than zero or more.

### 4.1.2 Item Element

FIREBASEXML contained the following child elements under its *Items* element:

- *attribute*
- *reference*
- *description*
- *heat\_of\_combustion*
- *initial\_mass*
- *data*

The new *Item* element can be seen in Figure 28.

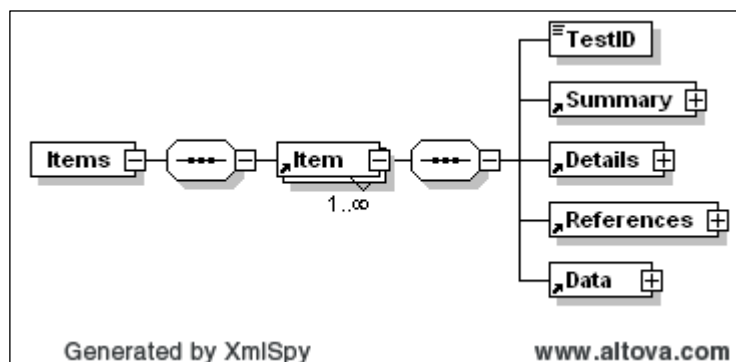


Figure 28: Item Element

Each fire test in the FIREBASEXML specification is differentiated from each other only by their *description* element. This means that it may be possible to have duplicate entries within the DBMS. To prevent this from occurring in the UCFIRE DBMS; it was decided that each item element carries a *TestID* element to distinguish it from other fire tests. These *TestID* elements must be unique for the UCFIRE document to be valid. Unfortunately the XML 1.0 specification *ID* element only allows for IDs beginning with a number and this was thought to be too restrictive so it was decided to validate this particular element separately to the validating XML parser.

The *attributes* element is not needed within UCFIRE and so it will be dropped. The *description* element of the FIREBASEXML will be split into two parts: a *Summary*

element and a *Details* element. The *Summary* element stores information that will be displayed within the first window of the UCFIRE DBMS User Interface.

The *Summary* element stores the test *Method*, the test *Standard* that the test was performed to and the *TestDate*. It will also provide a *Description* element to do much of the same work as the *description* element in the FIREBASEXML Schema. The *Summary* element contains space for a short description of the test. This element can be seen in Figure 29.

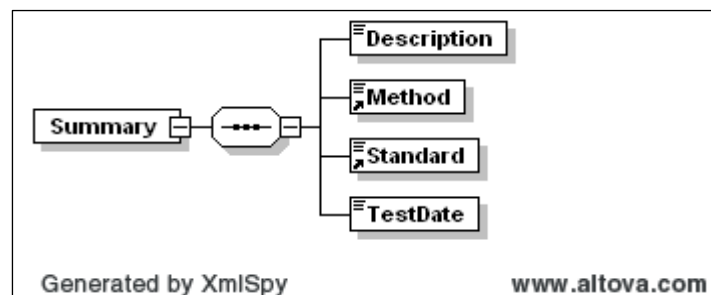


Figure 29: Summary Element

The *Details* element (Figure 30) will store much more detailed descriptive information about each fire test. This information will be initially hidden from the user in the User Interface as there is not enough screen room to display it. The data in the *Details* element will be accessed by clicking a button once the user has read the information contained within the *Summary* element. The *Details* element stores information about the person who performed the test, the sponsor of the test, and the organization which performed the test. If the test was one of many tests performed in a series this element also allows the total number of test performed, the current test number and the *TestSeriesID* to be stored as well. This *TestSeriesID* element will be particularly useful when locating collections of related fire tests. These were all required by the test standards discussed in the last section. They do not all need to be specified in a single test for the *Details* element to be considered valid by the validating XML parser.



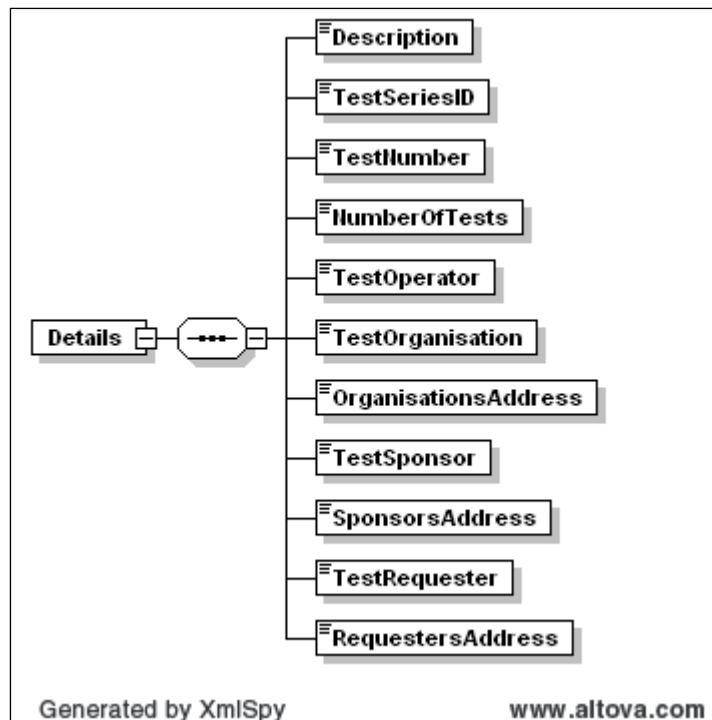


Figure 30: Details Element

The *References* element (Figure 31) from the FIREBASEXML specification was mostly unmodified when it was transferred to the UCFIRE specification.

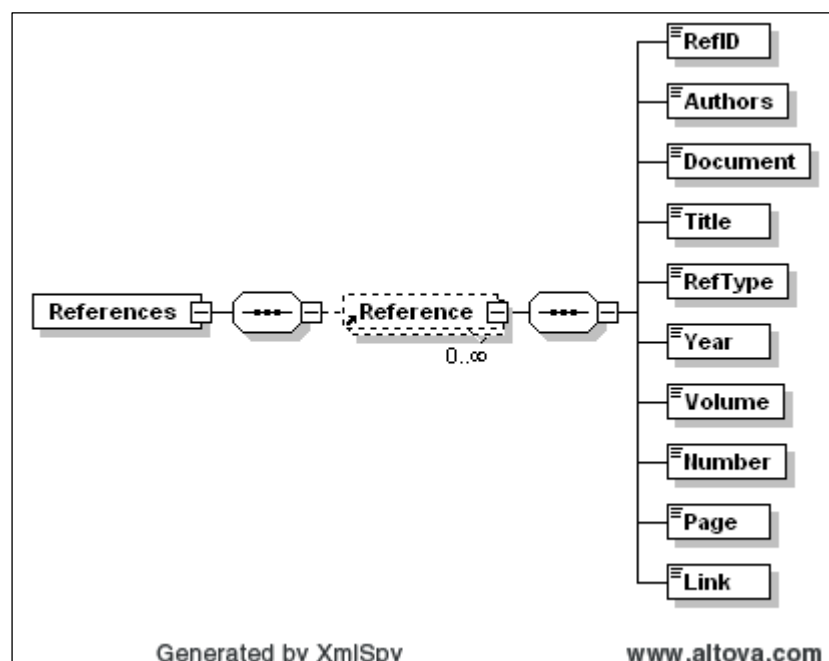


Figure 31: References Element

The FIREBASEXML specification required a *reference* element for all of its entries since all of them either came from external sources or have been published. This was

too restrictive and so it was decided to allow zero references to be stored within the UCFIRE specification since the specification is focussed on storing experimental fire test data and whether it has been published or not is deemed unimportant.

The FIREBASEXML *reference* element contained: *title*, *document*, *authors*, and *link* elements and these were all incorporated into the UCFIRE specification. In addition to this a *RefID* element was added to distinguish between different references, a *Reftype* element to distinguish between different types of references e.g. web documents, books, journal, unpublished results and so on. A *Volume*, *Year*, and a *Number* element was added to help identify journals and conference papers. To reduce complexity in the User Interface only one link was allowed per reference. It seemed unnecessary to include links to duplicate papers.

The *heat\_of\_combustion* and *initial\_mass* elements were taken away from the *item* element of FIREBASEXML and will be incorporated into a child element of the *Data* element of UCFIRE.

### 4.1.3 Data Element

The original FIREBASEXML *data* element could only store HRR data; the *Data* element for the new UCFIRE specification can store up to 10 categories of information.

The new *Data* element stores the following pieces of information:

- The environmental conditions of the test (*TESTPARAMETERS*). These parameters are all scalars.
- The materials involved in the test (*MATERIALS*).
- The *TIME* information for the test, including the time intervals at which measurements were made, time of flashover, flameout and ignition.
- Vector information can be stored in either *TIMESERIES* elements or *OTHERSERIES* elements.
- *LIFTPARAMETERS* which will contain the ignition and flame spread parameters as determined by the LIFT test.
- *IGNITABILITYPARAMETERS* which contains the thermo-physical parameters as determined by the ignitability test.
- *IMAGES* and *VIDEOS* elements which contain the names and descriptions of included image and video files.
- An *OBSERVATIONS* element which contains any pertinent observations made during the test.

The *Data* element is the most important element in a UCFIRE document as it contains all of the measured data for a particular fire test. The new *Data* element can be seen in Figure 32.

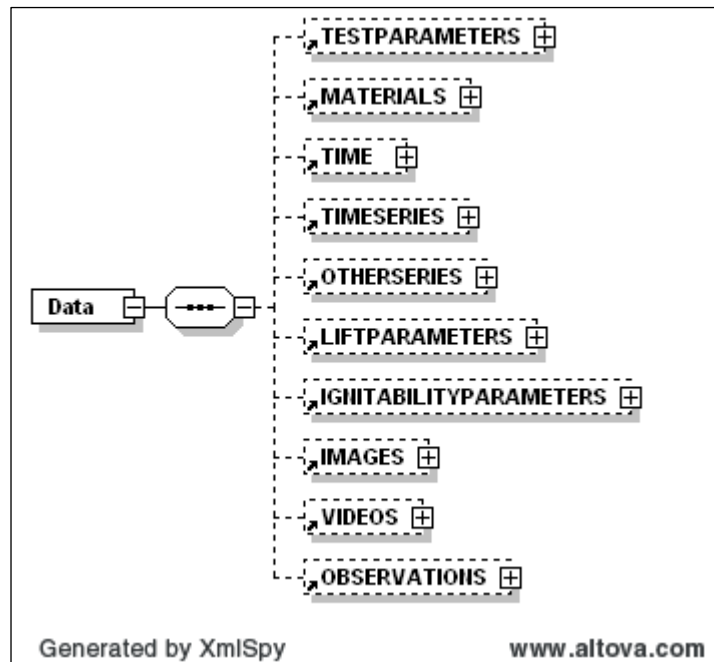


Figure 32: Data Element

In the UCFIRE Schema all the child elements of the *Data* element are optional and independent of each other. It is currently impossible to include dependencies between these elements based on the test method since XML is not a programming language: it cannot include conditional statements such as If method = “Cone Calorimeter” Then include *TIMESERES* element. However this limitation can be circumvented by adding additional XML validation rules to the UCFIRE Visual Basic.NET program. This will be explained in more detail at the end of this chapter.

The name of the *TIMESERIES* and *OTHERSERIES* elements had to be capitalized since they each contain *TimeSeries* and *OtherSeries* elements with a similar name and a different case system. All the other child items of the *Data* element were then capitalized to be consistent with these two elements.

#### 4.1.4 TESTPARAMETERS Element

The following test parameters were identified in the FDMS 2.0 specification:

- FRAME - Denotes if the edge flame was used (-).
- GRID - Denotes if the wire grid was used (-).
- IGNITOR – Ignitor used, yes/no (-).
- IGNTYPE – Ignition type (-).
- MOUNT - Specific means of mounting (-).
- ORIENT - Specimen orientation horizontal or vertical (-).
- PILOT – Indicates if ignition was piloted (-).
- RHCOND – relative humidity for specimen conditioning (%).
- TEMPCOND – temperature for specimen conditioning (°C).

Since the UCFIRE specification allows for the description of multiple materials to improve its usefulness as a repository of information for fire simulation software; it would be less useful to include *FRAME*, *GRID*, *MOUNT*, *ORIENT*, *RHCOND*, and *TESTCOND* elements within the *TESTPARAMETERS* element, as this would only refer to the test as a whole. This information would be better put into the *MATERIALS* element so that it could be specific for each material present in the experiment rather than generalised for the entire test.

It is unnecessary to state whether an *IGNITOR* has been used if the user has provided information on the type of *IGNITOR* used; for this reason an *IGNITOR* element was not included in the UCFIRE Schema but an *IGNTYPE* element was included. The new *IGNTYPE* element can currently be set to either: SPARK, CRIB, PILOT FLAME or NONE.

*RHTEST* and *TEMPTEST* elements of the FIREBASEXML Schema will be given the more descriptive names of *AMBHUMIDITY* and *AMBTEMP*.

The *TESTPARAMETERS* element will also store the heating flux the specimen was exposed to (only for LIFT and CONE tests). It was decided to specify the nominal surface area (only for CONE tests calculations) in the *TESTPARAMETERS* element

rather than in the *MATERIALS* element as the *MATERIALS* element can store multiple materials with different surface areas; so it was best to describe a single nominal surface area here to be used later in the data reduction algorithms.

The *TESTPARAMETERS* element can be seen in Figure 33.

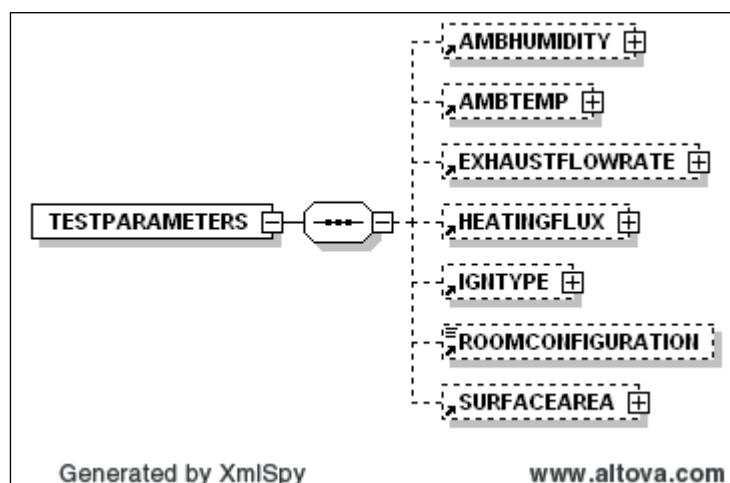


Figure 33: *TESTPARAMETERS* Element

#### 4.1.5 *MATERIALS* Element

The *MATERIALS* element allows for the storage of zero or more *MATERIAL* elements within the UCFIRE DBMS. The reason why multiple materials can be defined here is that when attempting to model an experiment, especially a Furniture Calorimeter, or Room/Corner test; the more information you have about materials present in the test the more realistic the simulation could potentially be.

Each *MATERIAL* element will have a unique *ID* element to distinguish it from other *MATERIAL* elements. Each *MATERIAL* element all also contain: *Description*, *Name*, *Location*, *Status*, *Manufacturer*, *ManufacturersAddress*, *SerialNumber*, and *DateSupplied* elements. These elements are all used as summary information to describe the material within the main page of UCFIRE's User Interface; other more detailed information about physical dimensions and thermo-physical parameters are hidden until the user requests them. The *Status* element is similar to the *PRIVATE* Field of the FDMS 2.0 specification and can hold one or two values: *PRIVATE* or

*PUBLIC*. If the material's *status* element is set to *Private* it will not be visible to a client accessing the file externally from a web server.

The *Manufacturer*, *ManufacturersAddress*, *SerialNumber*, and *DateSupplied* elements are required by the fire test standards discussed in Chapter 5 and must be included though they are allowed to hold empty strings if the user does not have the required information.

Material properties data fields in the FDMS 2.0 specification include:

- *AREA* – Specimen area ( $\text{m}^2$ ).
- *CONDUCT* – Conductivity ( $\text{kW/m.K}$ ).
- *DENSITY* – Density ( $\text{kg/m}^3$ ).
- *FRAME* – Denotes if an edge frame was used (-).
- *GRID* – Denotes if the wire grid was used (-).
- *INERTIA* – Thermal inertia ( $\text{kW}^2\text{s/m}^4\text{K}^2$ ).
- *LOCATION* – The location of the specimen.
- *MASSF* – Specimen mass at the end of the test (kg).
- *MASSI* – Specimen mass before the start of the test (kg).
- *MASSLOSS* – The total specimen mass loss (kg).
- *ORIENT* – The specimen orientation (-).
- *RHCOND* – The relative humidity for specimen conditioning (%).
- *RHTEST* – Relative humidity of the supply air for conducting the test (%).
- *TEMPCOND* – The temperature for specimen conditioning ( $^{\circ}\text{C}$ ).
- *THICK* – The thickness of the specimen (m).
- *TEMPTEST* – Temperature of the supply air for conducting the test ( $^{\circ}\text{C}$ ).
- *TIG* – The ignition temperature of the specimen ( $^{\circ}\text{C}$ ).
- *VOLUME* – The volume ( $\text{m}^3$ ).

These were all adopted into the UCFIRE specification, with minor changes made to names or units. For instance the *CONDUCT* data element's name was modified to *CONDUCTIVITY* so that it would be more descriptive. Also all the Temperature elements units were adjusted so that the SI units, Kelvin, were used instead of degrees Celsius.

Many of the items included in the list are required by different test standards such as *DateSupplied* element, but most of these elements are optional except for the *MaterialID*, *Description*, *Location* and *Status* elements by the UCFIRE DBMS. Some of the child elements present here are also included in the *LIFTPARAMETERS* element and the *IGNITABILITYPARAMETERS* element such as the *KPC* element.

The *AREA*, *VOLUME*, *THICK*, and *VOLUME* data elements of the FDMS specification were expanded to include the following:

- *DIAMETER* (m).
- *LENGTH* (m).
- *WIDTH* (m).
- *THICKNESS* (m).
- *HEIGHT* (m).
- *AREA* (m<sup>2</sup>).
- *VOLUME* (m<sup>3</sup>).

The following elements do not necessarily need to be measured experimentally they may come from external documents such as journal articles or conference papers and so they each contain a child element called *Reference* to contain this reference information:

- *ALPHA* (m<sup>2</sup>/s).
- *CONDUCTIVITY* (kW/mK).
- *DENSITY* (kg/m<sup>3</sup>).
- *MASSPUA* (kg/m<sup>2</sup>).
- *KPC* (kW<sup>2</sup>s/m<sup>4</sup>K<sup>2</sup>).
- *PHI* (kW<sup>2</sup>/m<sup>3</sup>).
- *QCRIT* (kW/m<sup>2</sup>).
- *TIG* (K).
- *SPHEAT* (kJ/m<sup>3</sup>K).

The *TIG*, *KPC*, and *QCRIT* elements are also shared by the *LIFTPARAMETERS* element. This means that after performing a LIFT test and determining the value for



*TIG*, *KPC*, and *QCRIT*; these values may be specified for the same material undergoing a different test.

To date no other DBMS has allowed for the storage of so many pieces of information about the materials involved in a fire test. The *MATERIALS* element can be seen in Figure 34.

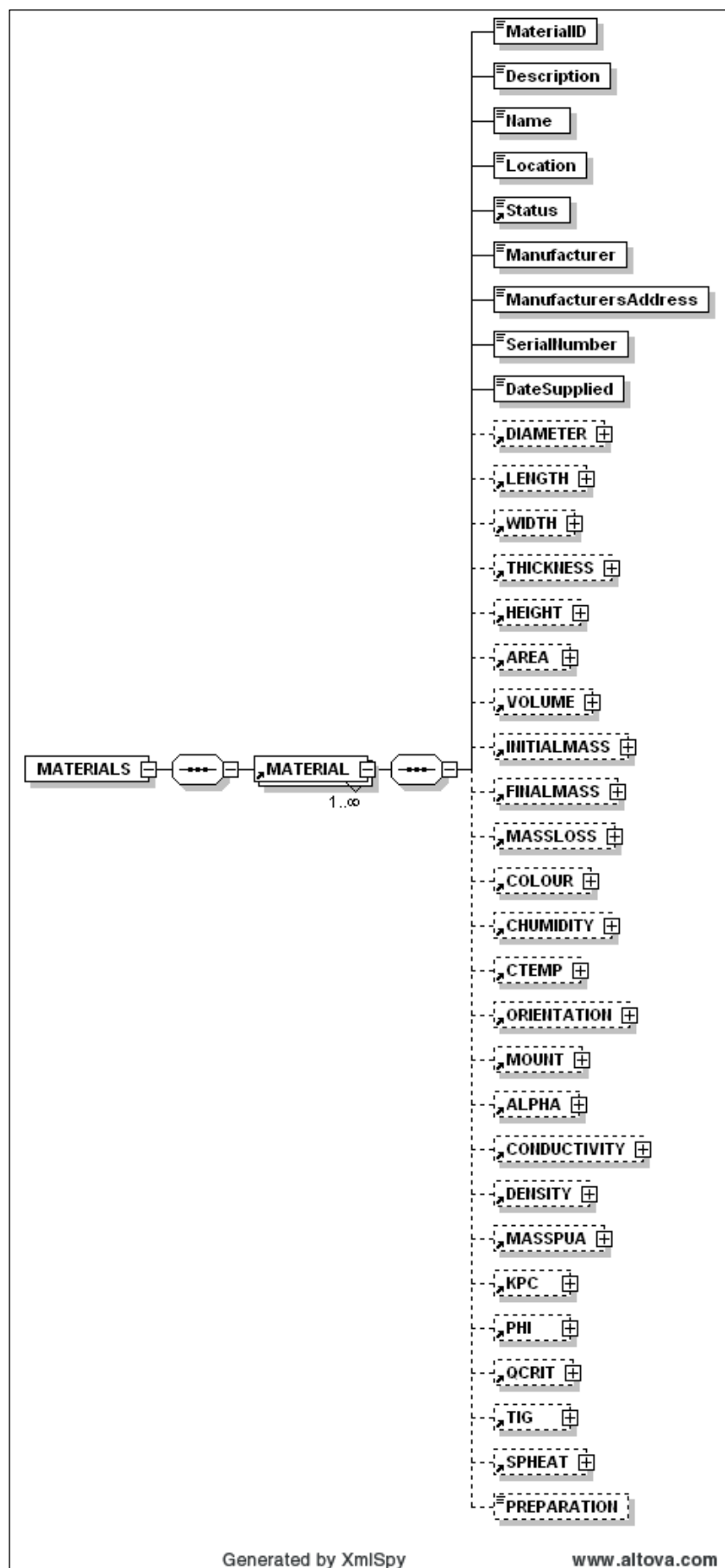


Figure 34: MATERIALS Element

### 4.1.6 TIME Element

The *TIME* element shown below in Figure 35 stores the time intervals that coordinate the vector data measuring instruments, and other time-relative pieces of information such as time of: ignition (*TIGN*), observed flashover (*FLASHOVER*) and flameout (*FLAMEOUT*).

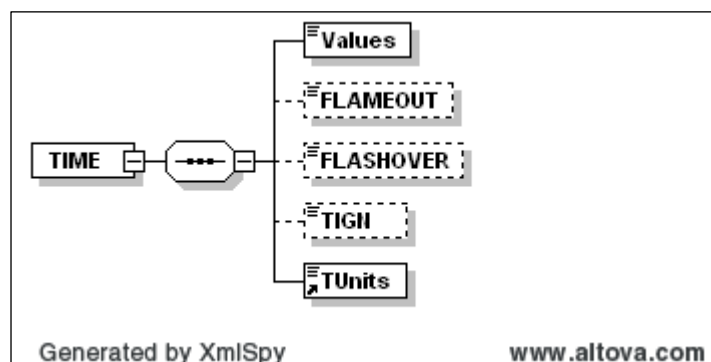


Figure 35: TIME Element

The *Values* element stores the time intervals over which the vector data measurements were recorded. This data is recorded as a comma separated line of values as shown in Figure 36.

```
<Values>0.0,1.0,2.0,3.1,4.1,5.2,6.2,7.3,8.3,9.3,10.4,11.4, ... </Values>
```

Figure 36: Comma Separated Vector Data

The *TIME* element is only stored in the UCFIRE document if one or more *TimeSeries* elements are present. The *TIMESERIES* element will be described in more detail in the next section.

#### 4.1.7 TIMESERIES and OTHERSERIES Elements

The *TIMESERIES* and *OTHERSERIES* elements store one or more sets of vector data recorded during a fire test. The main difference between the two is that time series are functions of time (the time data included in the *TIME* element) and other series are functions of another variable such as *DISTANCE* or *FLUX*.

The list of parameters that a time series or other series can reference can be seen below:

- *DISTANCE* - Distance from a reference point (m).
- *EXTCOEFF* - Extinction coefficient ( $\text{m}^{-1}$ ).
- *FLUX* - Heat flux ( $\text{kW/m}^2$ ).
- *fCO* - Gas yield of CO (kg/kg).
- *fCO2* - Gas yield of CO<sub>2</sub> (kg/kg).
- *fH2O* - Gas yield of H<sub>2</sub>O (kg/kg).
- *fHBR* - Gas yield of HBR (kg/kg).
- *fHCL* - Gas yield of HCL (kg/kg).
- *fHCN* - Gas yield of HCN (kg/kg).
- *fSOOT* - Gas yield of Soot (kg/kg).
- *FLAMEFRONT* - Position of the flame front (m).
- *HC* - Effective heat of combustion (MJ/kg).
- *HCPUA* - Effective heat of combustion per unit area ( $\text{MJ/kg.m}^2$ ).
- *HRR* - Heat release rate (kW).
- *HRRPUA* - Heat release rate per unit area ( $\text{kW/m}^2$ ).
- *HRRTOT* - Total heat released (MJ).
- *HRRTOTPUA* - Total heat released per unit area ( $\text{MJ/m}^2$ ).
- *MASS* - Mass loss the specimen (kg).
- *MASSFLOW* - Mass flow rate (kg/s).
- *MLR* - Mass loss rate (kg/s).
- *MLRPUA* - Mass loss rate per unit area ( $\text{kg/s.m}^2$ ).
- *OPTICALDENSITY* - Optical density of the smoke ( $\text{m}^{-1}$ ).
- *PRESSURE* - Pressure difference (Pa).

- *RSR* - Rate of smoke released ( $\text{m}^2/\text{s}$ ).
- *SEA* - Specific extinction area ( $\text{m}^2/\text{kg}$ ).
- *TSR* - Total smoke released ( $\text{m}^2$ ).
- *TIME* – Time for some action to occur (s).
- *TEMPERATURE* - Temperature measurement (K).
- *VOLFLOW* - Volumetric flow rate ( $\text{m}^3/\text{s}$ ).
- *XCO* - Mole fraction of CO (-).
- *XCO2* - Mole fraction of  $\text{CO}_2$  (-).
- *XH2O* - Mole fraction of  $\text{H}_2\text{O}$  (-).
- *XHBR* - Mole fraction of HBR (-).
- *XHCL* - Mole fraction of HCL (-).
- *XHCN* - Mole fraction of HCN (-).
- *XNOX* - Mole fraction of  $\text{NO}_x$  (-).
- *XO2* - Mole fraction of  $\text{O}_2$  (-).
- *XSOOT* - Mole fraction of Soot (-).

Note that in the UCFIRE Schema the units will not necessarily appear as they do above. The upper arrow bracket is used to denote power, for instance,  $\text{m}^2$  is  $\text{m}^{\wedge}2$  in the spreadsheet. This was done for practical reasons; brackets cannot be included in the units else the raw Excel spreadsheet will be read incorrectly by UCFIRE's input routines.

The *TIMESERIES* element can be seen in Figure 37.

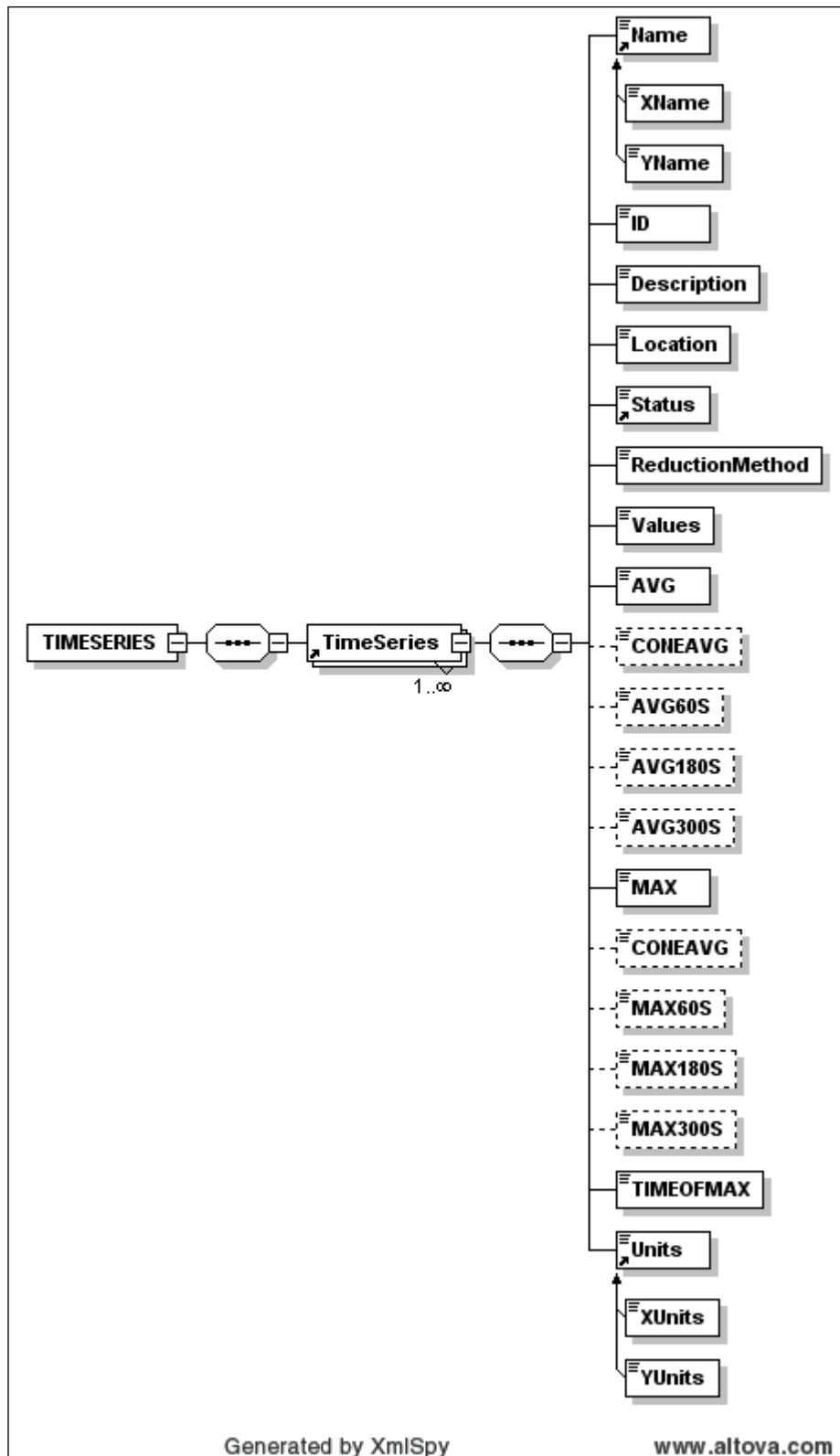


Figure 37: TIMESERIES Element

Each *TimeSeries* element has a unique *ID* element to distinguish it from other *TimeSeries* elements. The *Name* element indicates what data parameter is stored

within the *TimeSeries* element: for instance, if the *Name* element's value was *HRR* then the *TimeSeries* is storing Heat Release Rate data for a fire test.

The location where the measurement was taken can be stored in the *Location* element. Also the average, maximum, and the time of the maximum value are recorded for each time series. Optional elements include the average and maximum value of the time series over 60, 180 and 300 seconds after ignition, as per the requirements of some test standards. The calculation of averages will be explained in more detail in Chapter 7.

Sometimes it is necessary to record series of data which are not functions of time and these are referred to as other series. The *OTHERSERIES* element can be seen in Figure 38.

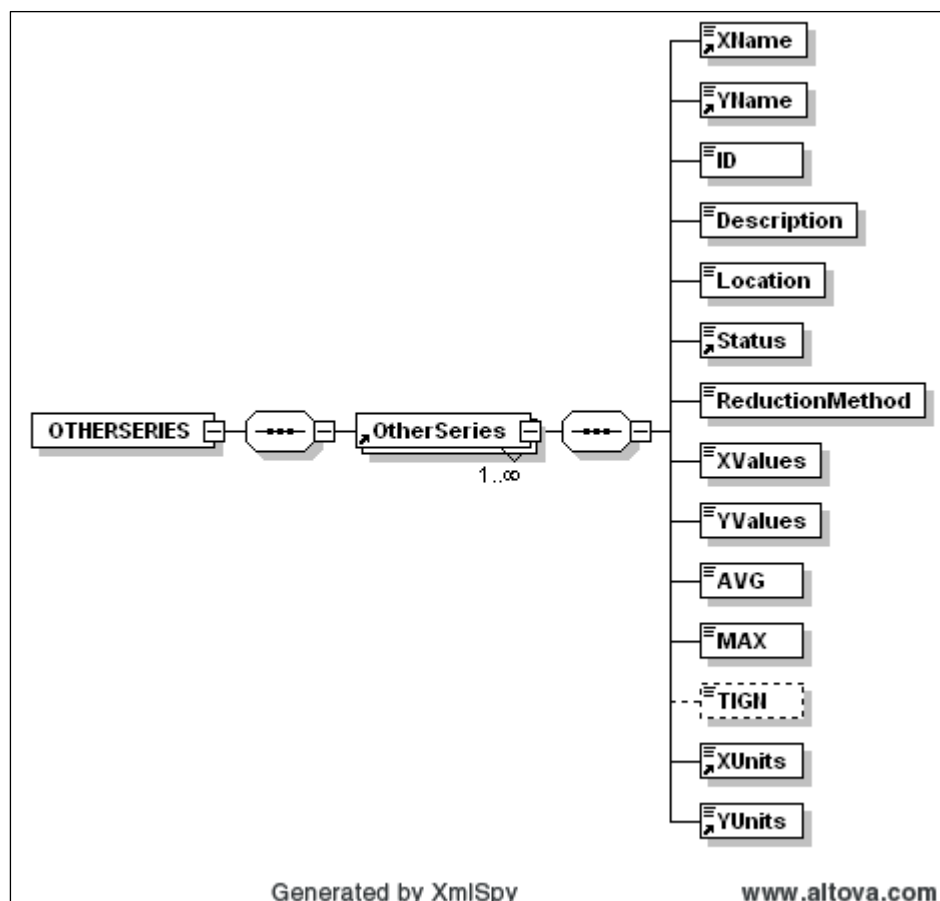


Figure 38: OTHERSERIES Element

The *OtherSeries* element is very similar to the *TimeSeries* element except it has additional space to store two vectors not one. These will each contain *XNAME* and *YNAME*, *XVALUES* and *YVALUES*, *XUNITS* and *YUNITS* elements.

It is necessary to check that each parameter of the *TimeSeries* and *OtherSeries* elements has the correct units and this can only be done with a set of additional validating rules to be discussed later in this chapter.



#### 4.1.8 LIFTPARAMETERS Element

The LIFT ignition and flame spread parameters calculated from the *OTHERSERIES* and *TESTPARAMETERS* elements and are then stored in the *LIFTPARAMETERS* element shown in Figure 39.

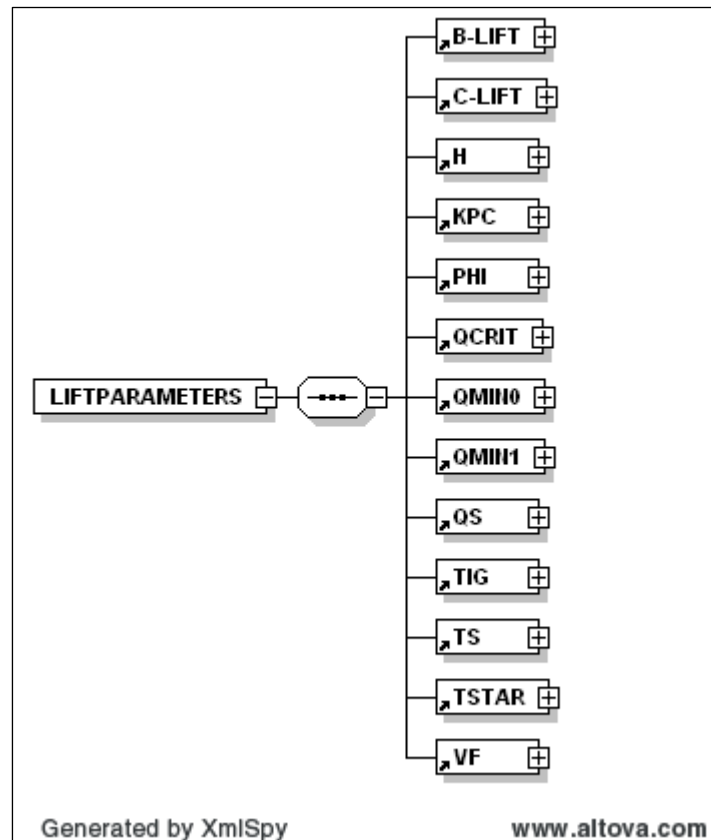


Figure 39: LIFTPARAMETERS Element

The *LIFTPARAMETERS* element contains all of the parameters recommended by the FDMS 2.0 specification, often with the same naming convention, as well as two additional quantities (*QMIN1* and *VF*). Since it was possible to calculate the minimum ignition flux in two different ways, the *QMIN* parameter of the FDMS specification was replaced with *QMIN0* and *QMIN1* data elements. The flame front velocity (*VF*) is also calculated and stored within the UCFIRE DBMS.

#### 4.1.9 IGNITABILITYPARAMETERS Element

The ISO ignition parameters calculated from the *OTHERSERIES* and *TESTPARAMETERS* elements are stored in the *IGNITABILITYPARAMETERS* element shown in Figure 40.

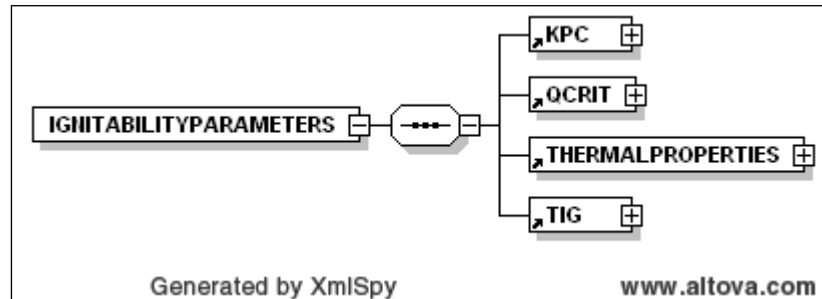


Figure 40: IGNITABILITYPARAMETERS Element

The *IGNITABILITYPARAMETERS* element can store the thermal inertia (*KPC*), critical heat flux (*QCRIT*), surface ignition temperature (*TIG*) and whether or not the material is thermally-thin or thermally-thick (*THERMALPROPERTIES*).

#### 4.1.10 IMAGES and VIDEO Elements

The UCFIRE Schema also allows for the storage of media. Images are stored under the *IMAGES* element, and videos are stored under the *VIDEOS* element. These elements can be seen in Figure 41 and Figure 42.

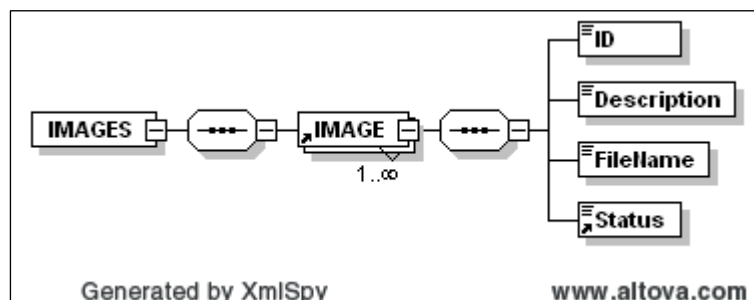
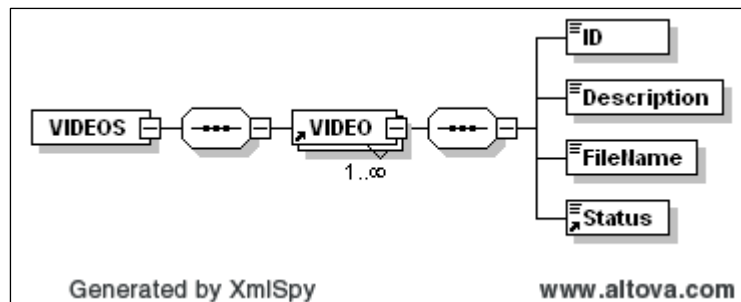


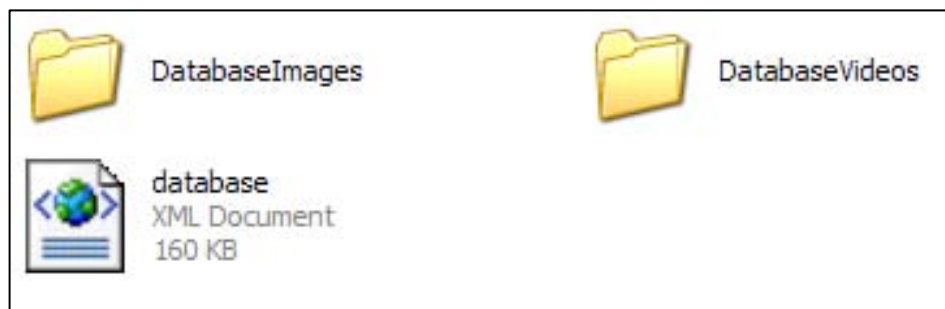
Figure 41: IMAGES Element



**Figure 42: VIDEOS Element**

Both elements store the *ID* of the image or video clip, a *Description* of the image or video clip and the *Filename* of the media file.

Unfortunately the media files cannot be stored directly within the XML UCFIRE document: they have to be stored in separate folders called *DatabaseImages* and *DatabaseVideos*. This data structure is shown below in Figure 43.



**Figure 43: Current UCFIRE Format**

It would be desirable to compress these three components into a single compressed folder so that individual elements could not be lost or corrupted. Unfortunately the .NET framework's GZIPstream and DeflateStream classes [28] only allow for the compression of files no larger than 4 Gigabytes. From the analysis in Chapter 12.2 of this thesis it can be seen that this file size limit may well be exceeded. Perhaps in the next version of the .NET framework this limiting file size will be increased, or a future developer of this software could create their own compression algorithm. For now it will be necessary to check to see if all the specified images and videos are present when opening a UCFIRE document with a set of additional XML validation rules programmed into the Visual Basic.NET program.

#### 4.1.11 OBSERVATIONS Element

The last element to be discussed is the Observations element that allows the user to record observations made during the fire test at specific times. This is shown in Figure 44.

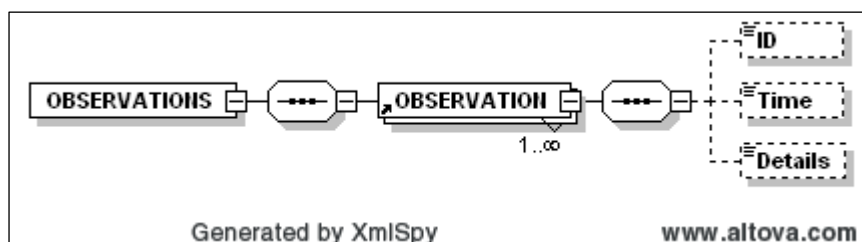


Figure 44: OBSERVATIONS Element

This element contains an *ID* element to distinguish between different observations since multiple observations may be made at each time instance. The *Time* element stores the time of occurrence that prompted the observation, and the *Details* element stores the notes containing the observation.

The complete UCFIRE Schema can be found in *Appendix B: UCFIRE Schema*.

## 4.2 Additional XML Rules

As discussed in the previous section XML is not a programming language: it cannot explicitly contain dependencies between elements and so it was necessary to create additional XML validation rules that run each time the document is validated. These rules include:

- Checking to see if all the *Item* element's *ID* elements are unique.
- Checking to see if the correct child elements of the *Data* element have been included. For instance, if a *TIMESERIES* element is present then there must be a corresponding *TIME* element present as well. Also Cone Calorimeter, Furniture Calorimeter, and Room/Corner tests must include at least one *TimeSeries* element.
- LIFT and ISO Ignitability Apparatus tests must include at least one *OtherSeries* element.

- Checking to see if all *TimeSeries* and *OtherSeries* units are correct.
- Checking to see that the all the media files specified in the *IMAGES* and *VIDEOS* elements are present.

The VB.NET code to perform these additional XML checks can be seen in Figure 45.

```
Sub CheckXML(ByVal doc As XmlDocument)
' This Sub checks the UCFIRE documents for additonal criteria beyond
that which the validating parser can check.

' Rule 1: Check to see if the fire test's IDs are all unique.
If CheckID(doc) = False Then
    Throw New Exception("Cannot have two items with the same ID")
End If

' Rule 2: Check to see if all data memebbers are present if they
should be.
If CheckRequisites(doc) = False Then
    Throw New Exception("Requisites Error")
End If

' Rule 3: Check to see if all TimeSeries and OtherSeries units are
correct.
If CheckUnits(doc) = False Then
    Throw New Exception("Units Error")
End If

' Rule 4: Check to see if all media files are present.
If CheckMedia(doc) = False Then
    Throw New Exception("Media Error")
End If

End Sub
```

**Figure 45: Additional XML Validation Rules**

## 5 Validation of the UCFIRE Data Structure

This chapter checks the standards reporting requirements of the relevant test standards that were described in Chapter 3 of this thesis with the UCFIRE DBMS data structure developed in Chapter 4 of this thesis.

The relevant test standards were:

- *ASTM E 1354 – 02* for the Cone Calorimeter [19].
- *NT FIRE 032* for the Furniture Calorimeter [20].
- *ISO 9705:1993(E)* for the Room/Corner Test [21].
- *BS467: Part 13: 1987* for the ISO Ignitability Apparatus Test [23].
- *ASTM E 1321-97a* for the LIFT Apparatus Test [26].

## 5.1 Cone Calorimeter (ASTM E 1354 – 02)

### 5.1.1 Fulfilment of ASTM E 1354 – 02 by UCFIRE

A table of the XML elements which fulfils the standard report requirements (listed in Chapter 4 of this thesis) can be seen below in Table 2.

Requirement	Corresponding UCFIRE element(s)	Compliance
1	<i>Material</i> → <i>SerialNumber</i>	Y
2	<i>Material</i> → <i>Manufacturer</i>	Y
3	<i>Summary</i> → <i>TestDate</i>	Y
4	<i>Details</i> → <i>Operator</i>	Y
5	<i>Materials</i> → ( <i>Name</i> , <i>Description</i> )	Y
6	<i>Materials</i> → <i>THICKNESS</i>	Y
7	<i>Materials</i> → <i>INITIALMASS</i> , <i>TIMESERIES</i> ( <i>MASS</i> )	Y
8	<i>Materials</i> → <i>COLOUR</i>	Y
9	<i>Materials</i> → <i>Preparation</i>	Y
10	<i>Materials</i> → ( <i>ORIENTATION</i> , <i>MOUNT</i> )	Y
11	<i>TESTPARAMETERS</i> → ( <i>HEATINGFLUX</i> , <i>EXHAUSTFLOWRATE</i> )	Y
12	<i>Details</i> → ( <i>TestNumber</i> , <i>NumberOfTests</i> )	Y
13	<i>TIME</i> → <i>IGNITION</i>	Y
14	<i>TIMESERIES</i> ( <i>HRRPUA</i> )	Y
15	<i>TIMESERIES</i> ( <i>HRRPUA</i> )	Y
16	<i>TIMESERIES</i> ( <i>HRRTOTPUA</i> )	Y
17	<i>TIMESERIES</i> ( <i>HC</i> )	Y
18	<i>TIMESERIES</i> ( <i>HC</i> )	Y
19	<i>Materials</i> → <i>FINALMASS</i> , <i>TIMESERIES</i> ( <i>MASS</i> )	Y
20	<i>TIMESERIES</i> ( <i>MLR</i> )	N
21	<i>TIMESERIES</i> ( <i>SEA</i> )	Y
22	<i>See Section 5.1.2</i>	-
23	<i>OBSERVATIONS</i>	Y
24	<i>OBSERVATIONS</i>	Y
25-33	<i>TimeSeries</i>	Y
34	<i>IMAGES</i> , <i>VIDEOS</i>	Y
35-40	<i>OBSERVATIONS</i>	Y

Table 2: Fulfilment of ASTM E 1354 – 02 by UCFIRE

Note that the formatting convention of this table is as follows:

- A → B or A → (B,C)

This means that the B child element of element A can store the desired data field or both the B and C child elements of element A can store the desired data field.

### **5.1.2 Compliance Issues**

Only partial compliance was achieved. For requirement 22 of Table 2, the average MLRPUA was recorded in  $\text{kg/m}^2\text{s}$  instead of the units required by the standard of  $\text{g/m}^2\text{s}$ : but this is consistent with the goal of using SI units for all quantities stored in UCFIRE.



## 5.2 Furniture Calorimeter (NT FIRE 032)

### 5.2.1 Fulfilment of NT FIRE 032 by UCFIRE

A table of the XML elements which fulfils the standard report requirements can be seen below in Table 3.

Requirement	Corresponding UCFIRE element(s)	Compliance
1	<i>Details → (TestOrganisation, OrganisationsAddress)</i>	Y
2	<i>Item → TestID, Summary → TestDate</i>	Y
3	<i>Details → (TestRequestor, RequestorsAddress)</i>	Y
4	<i>Details → Description</i>	Y
5	<i>TIMESERIES → Description</i>	Y
6	<i>Materials → Manufacturer</i>	Y
7	<i>Materials → (Name, Description)</i>	Y
8	<i>Materials → Density</i>	Y
9	<i>Materials → Description</i>	Y
10	<i>Materials → (Preparation, CHUMDIDITY, CTEMP)</i>	Y
11	<i>Summary → TestDate</i>	Y
12	<i>Summary → Method, Summary → Standard</i>	Y
13	<i>TIMESERIES (MLR)</i>	Y
14	<i>TIMESERIES (HRRTOT)</i>	Y
15	<i>TIMESERIES (fCO)</i>	Y
16	<i>TIMESERIES (fCO2)</i>	Y
17	<i>TIMESERIES (fSOOT)</i>	Y
18	<i>TIMESERIES (MASSFLOW)</i>	Y
19	<i>IMAGES → IMAGE</i>	Y
20	<i>TIMESERIES (HRR)</i>	Y
21	<i>TIMESERIES (HC)</i>	Y
22	<i>See Section 5.2.2</i>	-
23	<i>MATERIALS → Description</i>	N
24	<i>Details → Description</i>	Y
25	<i>Details → Description</i>	Y

Table 3: Fulfilment of NT FIRE 032 by UCFIRE

### **5.2.2 Compliance Issues**

Only partial compliance was achieved. For requirement 22 of Table 3, the production rates given in carbon monoxide and soot normalized versus measured rate of heat release and measured mass burning rate were not calculated. This is an optional requirement however and does not preclude the user from exporting the values from UCFIRE to Microsoft Excel and performing the analysis themselves and by excluding this element the UCFIRE Schema could be simplified.

### 5.3 Room/Corner Test (ISO 9705:1993(E))

#### 5.3.1 Fulfilment of ISO 9705:1993(E) by UCFIRE

A table of the XML elements which fulfils the standard report requirements by the UCFIRE can be seen in Table 4.

Requirement	Corresponding UCFIRE element(s)	Compliance
1	<i>Details → (TestOrganisation, OrganisationsAddress)</i>	Y
2	<i>Item → TestID, Summary → TestDate</i>	Y
3	<i>Details → (TestRequestor, RequestorsAddress)</i>	Y
4	<i>Summary → Description, Details → Description</i>	Y
5	<i>Details → Description</i>	Y
6	<i>Materials → (Manufacturer)</i>	Y
7	<i>Material → Name, Material → Description</i>	Y
8	<i>Material → MASSPUA, Material → Description</i>	Y
9	<i>Material → DateSupplied</i>	Y
10	<i>Material → Description, Material → Mount</i>	Y
11	<i>Material → Conditioning</i>	Y
12	<i>Summary -&gt; TestDate</i>	Y
13	<i>Summary → TestMethod</i>	Y
14	<i>TIMESERIES (FLUX)</i>	Y
15	<i>TIMESERIES (VOLFLOW)</i>	Y
16	<i>TIMESERIES (HRR)</i>	Y
17	<i>TIMESERIES (XCO, fCO)</i>	Y
18	<i>TIMESERIES (XCO2, fCO2)</i>	Y
19	<i>TIMESERIES (EXCOEFF, OPTICALDENSITY, SEA, fSOOT)</i>	Y
20	<i>IMAGE</i>	Y
21	<i>TIMESERIES (HRR)</i>	Y
22	<i>TIMESERIES (TEMPERATURE)</i>	Y
23	<i>TIMESERIES (TEMPERATURE)</i>	Y
24	<i>TIMESERIES (MASSFLOW)</i>	Y
25	<i>TIMESERIES (HRR)</i>	Y
26	<i>TIMESERIES (XSOOT)</i>	Y
27	<i>TIMESERIES (XNOX)</i>	Y
28	<i>TIMESERIES (XNCN, fHCN)</i>	Y
29	<i>Materials</i>	Y

**Table 4: Fulfilment of ISO 9705:1993(E) by UCFIRE**

## 5.4 ISO Ignitability Test (BS467: Part 13: 1987)

### 5.4.1 Fulfilment of BS467: Part 13: 1987 by UCFIRE

A table of the XML elements which fulfils the standard report requirements can be seen below in Table 5.

Requirement	Corresponding UCFIRE element(s)	Compliance
1	<i>OTHERSERIES (FLUX, TIME)</i>	Y
2	<i>OBSERVATIONS</i>	Y
3	<i>Details → (Organization, OrganisationsAddress)</i>	Y
4	<i>Details → (TestSponsor, SponsorsAddress)</i>	Y
5	<i>Material → Manufacturer</i>	Y
6	<i>Material → (Name, Description, ORIENTATION, THICKNESS, DENSITY, INITIALMASS)</i>	Y
7	<i>Material → Description</i>	Y
8	<i>Material → (THICKNESS, DENSITY)</i>	Y
9	<i>Material → (DateSupplied, Description, CHUMIDITY, CTEMP, PREPARATION)</i>	Y
10	<i>OBSERVATIONS</i>	Y

Table 5: Fulfilment of BS476: Part 13:1987 by UCFIRE

## 5.5 LIFT Test (ASTM E 1321-97a)

### 5.5.1 Fulfilment of ASTM E 1321-97a

A table of the XML elements which fulfils the standard report requirements can be seen below in Table 6.

Requirement	Corresponding UCFIRE element(s)	Compliance
1	<i>Summary</i> → <i>TestDate</i>	Y
2	<i>OBSERVATIONS</i>	Y
3	<i>Details</i> → ( <i>TestOrganisation</i> , <i>OrganisationsAddress</i> )	Y
4	<i>Material</i> → ( <i>Manufacturer</i> , <i>SerialNumber</i> , <i>THICKNESS</i> , <i>DENSITY</i> , <i>Description</i> )	Y
5	<i>Material</i> → ( <i>THICKNESS</i> , <i>DENSITY</i> , <i>CONDUCTIVITY</i> )	Y
6	<i>OTHERSERIES</i> ( <i>FLUX</i> , <i>TIME</i> )	Y
7	<i>LIFTPARAMETERS</i> → ( <i>QCRIT</i> , <i>QMIN0</i> )	Y
8	<i>LIFTPARAMETERS</i> → ( <i>TIG</i> )	Y
9	<i>LIFTPARAMETERS</i> → ( <i>B-LIFT</i> )	Y
10	<i>LIFTPARAMETERS</i> → ( <i>TSTAR</i> )	Y
11	<i>LIFTPARAMETERS</i> → ( <i>KPC</i> )	Y
12	<i>TESTPARAMETERS</i> → <i>HEATINGFLUX</i>	Y
13	<i>OTHERSERIES</i> ( <i>FLAMEFRONT</i> , <i>TIME</i> )	Y
14	<i>LIFTPARAMETERS</i> → ( <i>C-LIFT</i> )	Y
15	<i>LIFTPARAMETERS</i> → ( <i>QS</i> )	Y
16	<i>LIFTPARAMETERS</i> → ( <i>TS</i> )	Y
17	<i>LIFTPARAMETERS</i> → ( <i>PHI</i> )	Y

Table 6: Fulfilment of ASTM E 1321-97a by UCFIRE

## 5.6 Summary

Despite often conflicting reporting requirements of the different fire test standards; the new UCFIRE data structure fulfilled all but one requirement; that the average MLRPUA for the Cone Calorimeter test should be recorded in kg/m<sup>2</sup>s instead of the units required by the standard of g/m<sup>2</sup>s. This will be a minor inconvenience for the user; as they will be able to perform this conversion for themselves if they needed to and it was much better to use SI units consistently throughout the UCFIRE data structure.

## 6. UCFIRE Raw Excel File Format

There are two possible ways of loading raw test data into a DBMS; manually or automatically if the data is already stored in a separate computer file. Since the goal of this research was to create a DBMS that could automate the data reduction and storage process; the later was chosen. The full Microsoft Excel workbook format (.xls) was chosen over the comma delimited file format (.csv). The full format allows for multiple worksheets to be used instead of limiting the workbook to one worksheet which would make the file easier to read and easier to extract information from using Visual Basic.NET.

This Excel workbook includes the following worksheets:

- *Main.*
- *Parameters.*
- *Materials.*
- *TimeSeries.*
- *OtherSeries.*
- *Media.*
- *Obs.*
- *Refs.*

Note that the names of some of these worksheets were shortened so that they all would be immediately visible to the user. This layout is similar to data structure of the *Items* and *Data* elements of the UCFIRE Schema. This similarity will allow data to be sequentially extracted, reduced and placed into the UCFIRE XML document.

## 6.1 Exemplar Excel Worksheet

### 6.1.1 Main

The *Main* worksheet contains the fire test's unique ID and data for the *Summary* and *Details* elements. It seemed logical to place all of the information describing the fire test in the first worksheet. An excerpt from an exemplar *Main* worksheet can be seen in Table 7.

<u>Summary</u>	
TestID:	C7S1
Description:	Chair C7S1 Single seater chair
Method:	Furniture Calorimeter
Standard:	ASTM E 1537-02
TestDate:	2/05/1999
<u>Details</u>	
Description:	
TestSeriesID:	
TestNumber:	
NumberOfTests:	
TestOperator:	
TestOrganization:	UOC
OrganisationsAddress:	Christchurch, New Zealand
TestSponsor:	
SponsorsAddress:	
TestRequester:	
RequestersAddress:	

**Table 7: Exemplar Main Worksheet**

This worksheet can be seen in more detail in *Appendix C: Exemplar Excel Workbook* of this thesis.

## 6.2.2 Parameters

The *Parameters* worksheet contains all the data that could be contained with the *TESTPARAMETERS* element of the UCFIRE specification. It is used to store temporary scalar values (LIFT preheat times) that cannot be easily stored in the *OtherSeries* worksheet. Since there is nothing but empty rows below the last *Preheat* time; additional preheat times values can be recorded as necessary as extra rows beneath the last *Preheat* time value.

This sheet is the best place to store the scalar data for the *FLAMEOUT*, *FLASHOVER* and *TIGN* child elements of the *TIME* element. An excerpt from an exemplar *Main* worksheet can be seen in Table 8.

<u>Parameter</u>	<u>Value</u>	<u>Units</u>	<u>Options</u>
AMBHUMIDITY	60	%	
AMBTMP	283	K	
EXHAUSTFLOWRATE		m <sup>3</sup> /s	
HEATINGFLUX		kW/m <sup>2</sup>	
IGNTYPE		-	SPARK, NONE
SURFACEAREA		m <sup>2</sup>	
FLAMEOUT		s	
FLASHOVER		s	
TIGN		s	
<u>LIFT Test Parameters</u>			
Preheat Time		s	
Preheat Time		s	
Preheat Time		s	

**Table 8: Exemplar Parameters Worksheet**

This worksheet can be seen in more detail in *Appendix C: Exemplar Excel Workbook* of this thesis.



### 6.2.3 Materials

Each material data field is included as a new column heading, so new materials can be added as new rows to the Materials datasheet. As the materials properties list is very extensive an excerpt from the dataset cannot be shown here but a list of the corresponding columns can be given. The columns include the following:

- *Description.*
- *Name.*
- *Location.*
- *Status.*
- *Manufacturer.*
- *ManufacturersAddress.*
- *SerialNumber.*
- *DateSupplied.*
- *DIAMETER (m).*
- *LENGTH (m).*
- *WIDTH (m).*
- *THICKNESS (m).*
- *HEIGHT (m).*
- *AREA (m<sup>2</sup>).*
- *VOLUME (m<sup>3</sup>).*
- *INITIALMASS (kg).*
- *FINALMASS (kg).*
- *COLOUR.*
- *CHUMIDITY (%).*
- *CTEMP (K).*
- *ORIENTATION.*
- *MOUNT.*
- *ALPHA (m<sup>2</sup>/s) + Reference.*
- *CONDUCTIVITY (kW/mK) + Reference.*
- *DENSITY (kg/m<sup>3</sup>) + Reference.*
- *MASSPUA (kg/m<sup>2</sup>) + Reference.*

- *KPC* ( $\text{kW}^2\text{s/m}^4\text{K}^2$ ) + *Reference*.
- *PHI* ( $\text{kW}^2/\text{m}^3$ ) + *Reference*.
- *QCRIT* ( $\text{kW}/\text{m}^2$ ) + *Reference*.
- *TIG* ( $\text{K}$ ) + *Reference*.
- *SPHEAT* ( $\text{kJ}/\text{m}^3\text{K}$ ) + *Reference*.
- *PREPARATION*.

These were primarily grouped based on commonality and secondly alphabetically. For instance: all of the physical dimensions were grouped together, all the mass information was grouped together and all the thermal physical parameters were grouped together.

The *PREPARATION* element was placed last so that if the user entered a very long description (especially one without carriage returns) it would not overrun and block other parameters.

Part of this worksheet can be seen in *Appendix C: Exemplar Excel Workbook* of this thesis.

## 6.2.4 Time Series

The *TimeSeries* worksheet contains information all of the data that could be contained with the *TIMESERIES* element of the UCFIRE specification. An excerpt from an exemplar *TimeSeries* worksheet can be seen in Table 9.

Time Series:		TIME	HRR	XO2	XCO2	XCO
Description:		Description	Calculated	Molar Fraction	Molar Fraction	Molar Fraction
Location:			Duct	Duct	Duct	Duct
Reduction Method:			NONE	NONE	NONE	NONE
Status:		Public	Public	Public	Public	Public
Units:		s	kW	-	-	ppm
		-180	0.5	0.2096	0.000353116	7
		-178.9	0.9	0.2095	0.000353116	7
		-177.8	0.5	0.2094	0.000361335	7
		-176.7	0.5	0.2096	0.000353116	7
		-175.5	-0.9	0.2095	0.000353116	8
		-174.4	-0.3	0.2096	0.000353116	6
		-173.3	1.8	0.2094	0.000361335	7

**Table 9: Exemplar TimeSeries Worksheet**

The order of each column (*TimeSeries*) does not matter, as the individual *TimeSeries* elements will be arranged alphabetically inside the XML UCFIRE document. However, the first column must contain the *TIME* vector data, each column must have the correct units specified and the *Status* element must be set to either *Public* or *Private*. The *Location* and *ReductionMethod* elements can be left blank but for completeness should be filled out in full. At this point in time the *ReductionMethod* field is only for the user to include the equations used to calculate the heat release rate (these vary depending on whether CO or CO<sub>2</sub> etc. was measured). Later the *ReductionMethod* element is used for derived *TimeSeries* and *OtherSeries* elements to store the type and the parameters of the reduction algorithm used on its raw data.

This worksheet can be seen in more detail in *Appendix C: Exemplar Excel Workbook* of this thesis.

## 6.2.5 Other Series

The *OtherSeries* worksheet contains information about all of the data that could be contained with the *OTHERSERIES* element of the UCFIRE specification. An excerpt from an exemplar *OtherSeries* worksheet can be seen in Table 10.

Other Series:		FLUX	TIME		DISTANCE	FLUX
Description:		IgnitionData	IgnitionData		FluxProfile	FluxProfile
Location:		Specimen	Specimen		Specimen	Specimen
Status:		Public	Public		Public	Public
Units:		kW/m^2	s		m	kW/m^2
		12.500	No ign.		0.050	24.198
		15.000	No ign.		0.100	23.746
		17.500	409.000		0.150	22.000
		20.000	309.000		0.200	19.822
		30.000	122.000		0.250	17.254
		40.000	73.000		0.300	14.445
		50.000	37.700		0.350	11.225
		60.000	25.400		0.400	8.052
					0.450	5.975
					0.500	3.912
					0.550	2.812
					0.600	1.912
					0.650	1.323
					0.700	0.917
					0.750	0.737

**Table 10: Exemplar OtherSeries Worksheet**

The order of each column (*TimeSeries*) does not matter, as the individual *TimeSeries* elements will be automatically arranged alphabetically inside the XML UCFIRE document.

Each column must have the correct units specified and the *Status* data Field must be set to either *Public* or *Private*. The *Location* data field can be left blank but for completeness should be filled out in full. It was decided to restrict the user from completing the *ReductionMethod* data field since at this stage it only applies to the equations used to calculate the HRR equations for a *TimeSeries* element.

This worksheet can be seen in more detail in *Appendix C: Exemplar Excel Workbook* of this thesis.

### 6.2.6 Media

The *Media* worksheet contains information about all of the data that could be contained within the *IMAGES* or *VIDEOS* element of the UCFIRE specification. An excerpt from an exemplar Media worksheet can be seen in Table 11.

<u>Description</u>	<u>Type</u>	<u>Status</u>	<u>FilePath</u>
Chair Fire	VIDEO	Public	c:\Data\Example1.avi
Chair Fire	IMAGE	Public	c:\Data\Example1.jpg

**Table 11: Exemplar Media Worksheet**

Since both images and videos are recorded here it was necessary to distinguish between the two by including the *Type* column; which indicates whether the file is an image file or a video file. This worksheet can be seen in more detail in *Appendix C: Exemplar Excel Workbook* of this thesis.

### 6.2.7 Obs.

The *Obs.* worksheet contains information about all of the data that could be contained within the *OBSERVATIONS* element of the UCFIRE specification. An excerpt from an exemplar *Obs.* worksheet can be seen in Table 12.

<u>Observations</u>	
<u>Time</u>	<u>Details</u>
-	The test results relate only to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the products in use.

**Table 12: Exemplar Obs. Worksheet**

### 6.2.8 Refs.

The *Refs.* worksheet contains information about all of the data that could be contained within the *REFERENCES* element of the UCFIRE specification. This worksheet is shown in *Appendix C: Exemplar Excel Workbook* of this thesis.

## 7 Reduction Techniques for Fire Test Data

This chapter explains how fire test data from a raw Excel spreadsheet is reduced and stored within the UCFIRE DBMS. Chapter 3 of thesis examined the reporting requirements of five standard fire tests and it was noted that there was a number of derived values that had to be calculated from the raw data contained within the Excel workbook discussed in Chapter 6.

These derived values include:

- Mass Loss Rate (MLR) and Mass Loss Rate Per Unit area (MLRPUA). The MLRPUA is only required for the Cone Calorimeter test.
- Total Heat Release (HRRTOT) and Total Heat Released Per Unit Area (HRRTOTPUA). The HRRTOTPUA is only required for the Cone Calorimeter test.
- Effective Heat of Combustion (HC).
- Total Smoke Released (TSR). This is only required by the FURN test.
- Gas yields .
- Carbon monoxide/carbon dioxide molar ratio. This is only required by the Furniture Calorimeter test.
- LIFT ignition and flame spread parameters.
- ISO Ignitability Apparatus ignition parameters.

The MLR is required for several calculations:

- Effective Heat of Combustion (HC).
- Gas yields.
- Soot yield.

These calculations would be laborious to do by hand but they are very amenable to automation by programs.

No standard currently requires the calculation of the soot yield but it was decided to include in the list of reduction algorithms for completeness.

## 7.1 General Procedure

As mentioned in the last section data is taken from the Excel Workbook, and then processed and stored as XML in a sequential fashion. If a calculation requires more than one time series or other series this data is stored away in memory until all pertinent parts have been collected. If all the components of a calculation are not present then the calculation will not proceed. The general procedure for adding a new data item can be seen below in Figure 46.

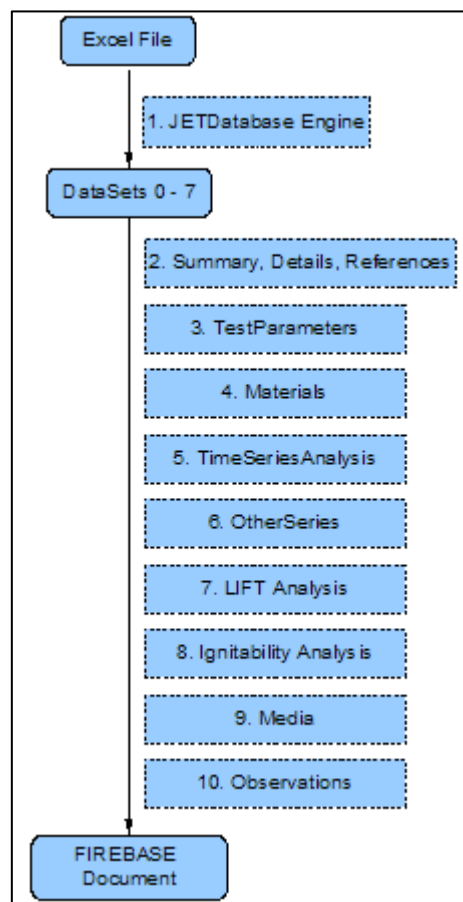


Figure 46: General Procedure for Adding a New Data Item

General Procedure:

1. Microsoft's JetDatabase engine is used to access the Microsoft Excel workbook and to fill the datasets 0-7 with data.
2. The summary, details and references information is written to the UCFIRE DBMS.
3. The test parameters for the fire test are written to the UCFIRE DBMS.
4. Information about each specified material is written to the UCFIRE DBMS.

5. Basic time series data is written to the UCFIRE DBMS and further analysis may be performed.
6. Basic other series data is written to the UCFIRE DBMS and some of this data may be accessed again when performing LIFT or Ignitability Apparatus analysis.
7. Data taken from the *OtherSeries* and *Parameters* worksheets of the Excel workbook are used to performed LIFT data reduction. The LIFT parameters and corresponding correlations are written to the UCFIRE DBMS.
8. Data taken from the *OtherSeries* and *Parameters* worksheets of the Excel workbook are used to perform ignitability data reduction. The ignitability parameters and corresponding correlations are written to the UCFIRE DBMS.
9. Images and video clips are written to the UCFIRE DBMS.
10. Any observations related to the fire test are recorded within the UCFIRE DBMS.

The Microsoft JetDatabase engine was chosen over Microsoft Excel COM component for the following reasons:

- The JetDatabase engine offered a tremendous performance advantage over using the Excel COM module. Accessing data through the legacy COM interface can result in performance degradation of 50 times compared with native VBA code [29]. Unfortunately the JetDatabase engine treats all the data contain in the excel spreadsheet as strings; so each number will only be recorded with the visible precision; hidden precision in the Excel workbook will be lost. This should not be a problem for most users, and this has been noted in UCFIRE's release notes.
- Simpler interface than the COM component.
- Memory is managed within the .NET framework unlike the COM interface where memory has to be managed explicitly to prevent memory leaks.
- Microsoft warns developers against using the Excel COM components on web servers for security reasons.

The potential new data item is stored in a separate XML file (*tempdata.xml*) to the main UCFIRE XML file. This is so that it can be automatically validated by the XML reader object when it is read into memory. If the temporary instance of the UCFIRE



document is invalid it will be rejected without affecting the main UCFIRE document. The additional XML validation rules are applied after the temporary XML UCFIRE document has been merged with the main UCFIRE XML document as one of XML validation rules (*ItemID*) can only be checked when it has access to complete set of the Item *ID* elements.

## **7.2 Exemplar Data Used**

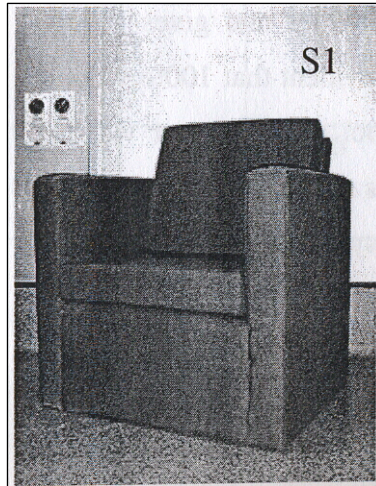
The data reduction algorithms to be discussed later in this chapter will need to be performed on real fire test data to evaluate their performance.

### **7.2.1 Cone Calorimeter**

Pau [30] has been performing a number of Cone Calorimeter tests at the University of Canterbury as part of his research thesis. These tests have been performed to the strict requirements of *ASTM E 1353-02*, and the reason why these will be used to evaluate the time series data reduction algorithms is because he has made light-extinction measurements with a Helium-Neon laser which will allow the Soot yield algorithm to be evaluated. Pau has performed a number of tests but his 25mm MDF and 25mm PMMA specimens will be used as exemplar data to examine the data reduction algorithms.

### **7.2.2 Furniture Calorimeter**

Hill [31] performed a number of New Zealand upholstered furniture fire tests under the Furniture Calorimeter in 2003. The author has accessed to two of his tests; B6S1 and C7S1. The S1 component of the test names indicate that these tests were for angled back single seater chairs with upholstered arms and legs. Figure 47 shows a picture of this chair.



**Figure 47: S1 Type Upholstered Chairs [31]**

These chairs were custom made out of Radiata pine, polyurethane, and a wool/nylon based fabric.

The names of these Furniture Calorimeter tests were the impetus to validate the item *ID* elements of the UCFIRE DBMS separately to the standard validating parser since XML's *ID* element can only stores ID beginning with a number, and these test IDs began with a letter.

### **7.2.3 Room/Corner Test**

The Room/Corner test does not require any different data reduction algorithms to the Furniture and Calorimeter tests and will not be considered any further in this thesis.

### **7.2.4 Ignitability Apparatus**

The author performed a number of ISO Ignitability tests on a polyurethane foam-fabric composite in 2006. One of these tests will be used to validate UCFIRE data reduction algorithms.

### 7.2.5 LIFT Apparatus

Merryweather [25] performed a number of small scale LIFT experiments and RIFT experiments (a cheaper and more efficient alternative to the LIFT test) as part of his objective to compare the performance of the LIFT and RIFT apparatuses. These experiments were performed on a number of wood based specimens. Six of these specimens were selected and are shown in Table 13.

Material	Thickness (mm)	Density (kg/m <sup>3</sup> )
Plywood	17	487
Particle Board	20	745
Medium Density Fibreboard	18	620
Hardboard	5	819
NZ Macrocarpa	20	514
NZ Rimu	20	660

**Table 13: Merryweather's LIFT Specimens**

There appears to be some human error involved in Merryweather's data reduction, and this was part of the motivation to produce the UCFIRE DBMS; so there was a need to use some data produced by another organisation to prove the efficacy of the LIFT data reduction algorithms. Unfortunately as Merryweather [25] noted the LIFT test is much more expensive than other fire tests such as the Cone Calorimeter test and only 20 LIFT apparatuses were present in the World in 1995, and this meant that there may be a small pool of useable published results to draw upon. It was also found that very few papers include tabulated ignition and flame spread results that could be used to validate their results. However Sumathipala and Monette [32] performed some LIFT experimental ignition results on six different materials according to the *ASTM E 1351-90* standard [33] and provided tabulated LIFT ignition data.

These materials are shown in Table 14.

Specimen	Thickness (mm)
Plywood	12
Fire Retardant (FR.) Plywood	12
Gypsum Wallboard	16
Composite Board	11
Polystyrene Foam	22
Polyurethane Foam	22

**Table 14: Sumathipala and Monette's LIFT Specimens**

The Polystyrene Foam and Polyurethane Foam specimens were deemed unsuitable for the LIFT test by Sumathipala and Monette [32] and so they will not be considered any further. It should be noted that these experiments were performed according to the *ASTM E 1351-90* standard [33] and not the *ASTM E 1351-97a* standard [26] but this should not affect the underlining data reduction process. The Fire Retardant Plywood and the Composite Board specimens exhibited inconsistent behaviour and so will not be considered any further.

Babrauskas and Wetterlund's [34] published LIFT flame spread data which could be used to validate the application of the data reduction algorithms to the Flame Spread correlation but unfortunately their flame spread measurements were not made in intervals of 25 mm as required by *ASTM E 1321-97a* but 50 mm intervals; so these measurements had to be linearly interpolated to produce values in 25 mm increments. Also Babrauskas and Wetterlund did not tabulate their ignition data so their Thermal Response correlations had to be digitized and then converted into meaningful quantities for entry into UCFIRE.

These materials are shown in Table 15.

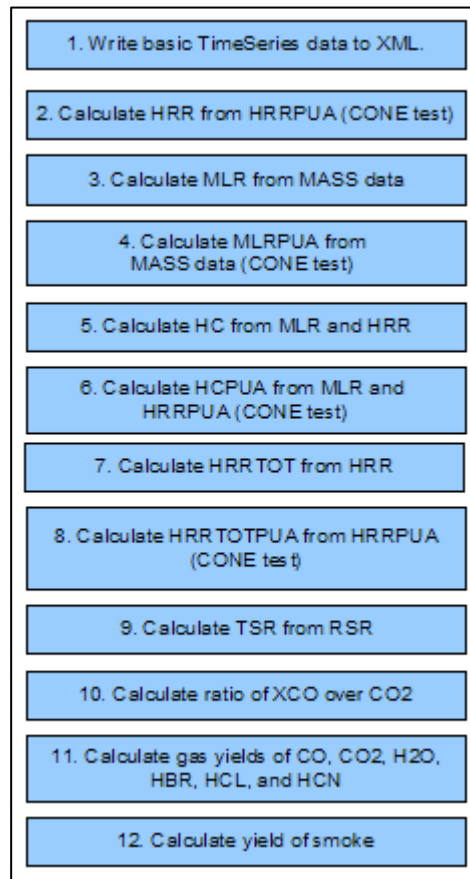
<b>Specimen</b>	<b>Thickness (mm)</b>
Wood Particle Board	19
FR PU Foam	40
Black PMMA	10
Insulating Fibreboard	13
Acrylic Pile fabric/HR Foam	50
Cotton/Kevlar/HR PU Foam	50

**Table 15: Babrauskas and Wetterlund's LIFT Specimens**

All of these materials will be examined within this thesis except for the Wood Particle Board specimen which showed inconsistent behaviour.

### 7.3 Time Series Data Reduction

Figure 48 shows the steps needed to reduce time series data. This is done sequentially and each step is optional and is entirely dependent on the requisite data being available. Some steps such as steps 2, 4, 6 and 8 will only be performed for Cone Calorimeter tests.



**Figure 48: Time Series Reduction**

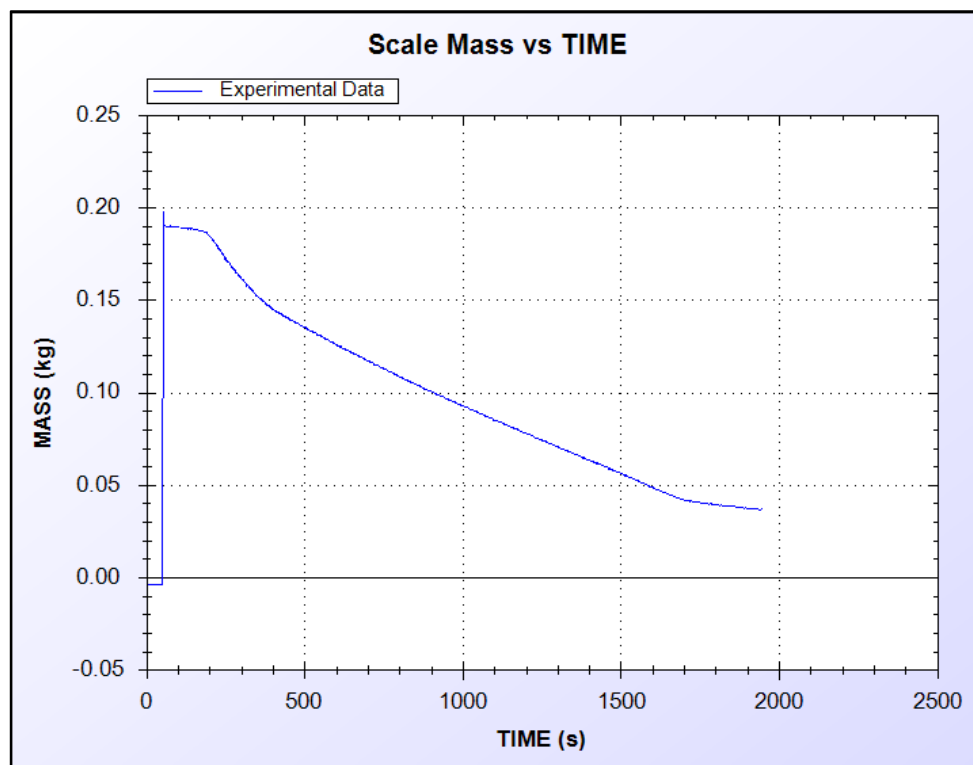
Steps 3-12 will be explained in detail in next section of this thesis.

### 7.3.1 Mass Loss Rate

This section explains how step 3 of Figure 48 is performed. The Mass Loss Rate (MLR) is derived from the mass reading for a specimen undergoing combustion. The MLR is the time rate of change in mass of the specimen as it undergoes combustion.

The MLR algorithms will be evaluated with data taken from the B6S1 and C7S1 upholstered chair tests performed in the Furniture Calorimeter by Hill [31], and a 25 mm MDF test and a 25 mm PMMA test performed in the Cone Calorimeter by Pau [30].

The mass curves for the 25 mm MDF and PMMA specimens can be seen in Figures 49 and 50, and the mass curves for B6S1 and C7S1 can be seen in Figure 51 and 52.



**Figure 49: Mass Curve for MDF (25mm)**

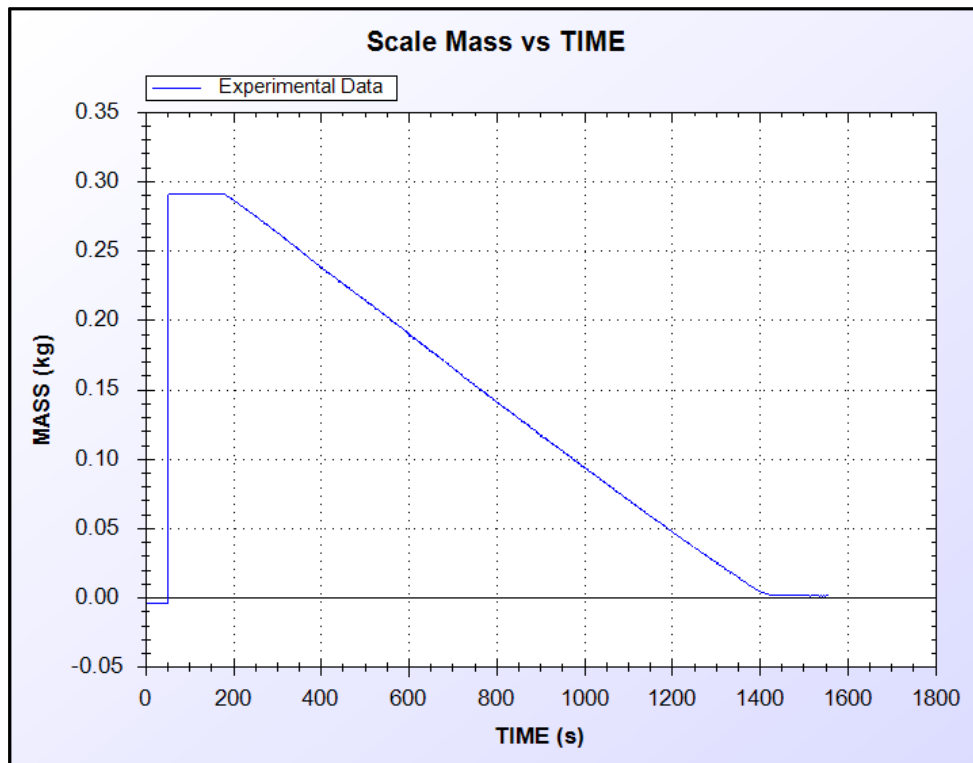


Figure 50: Mass Curve for PMMA (25mm)

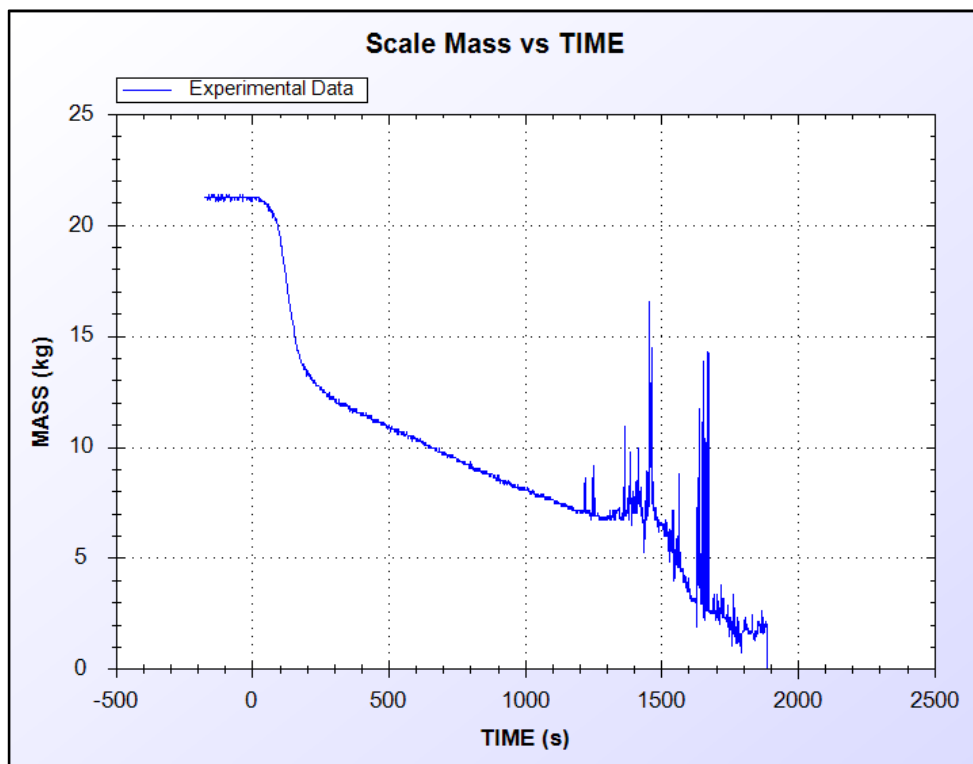
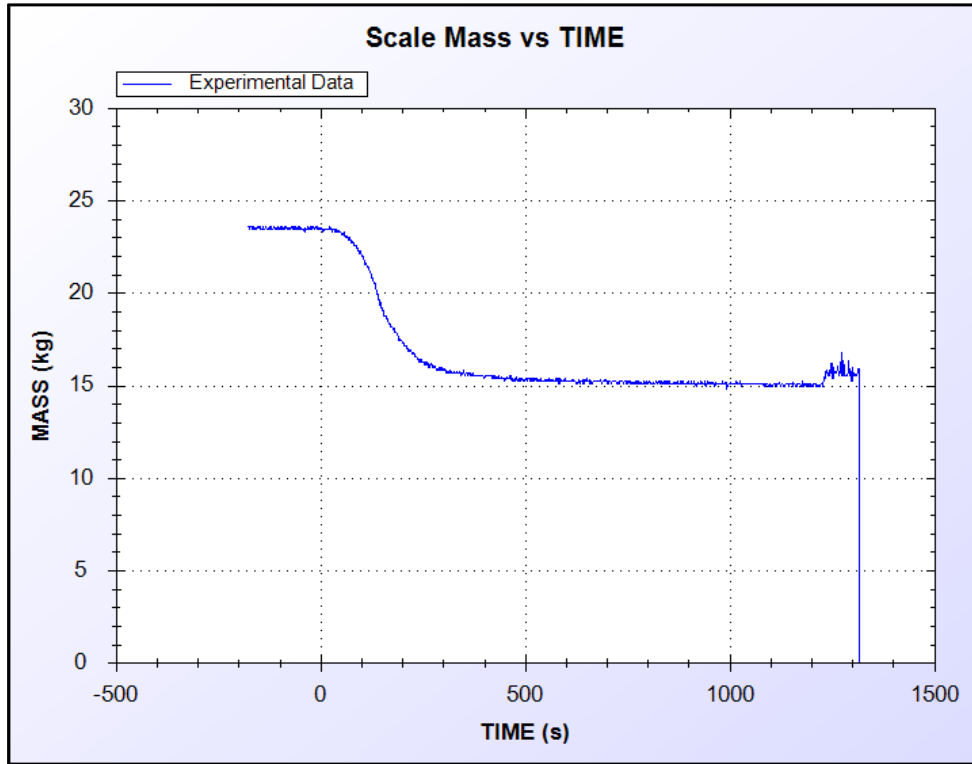


Figure 51: Mass Curve for B6S1





**Figure 52: Mass Curve for C7S1**

It is interesting to note that the mass curve for B6S1 (Figure 51) is very noisy especially at 1200 s when the chair starts to break up, unlike C7S1's mass curve (Figure 52) which is comparably noise free; it even collapses smoothly. An autonomous MLR algorithm must be able to cope with any and all of these scenarios.

One method of calculating the MLR is given by the Cone Calorimeter standard *ASTM E 1354 – 02* [19] as a set of equations produced by performing 5-point numerical differentiation on the mass samples. These expressions can be seen in Equations 7.1-7.5.

For the first scan:

$$-\left[\frac{dm}{dt}\right]_{i=0} = \frac{25m_0 - 48m_1 + 36m_2 - 16m_3 + 3m_4}{12\Delta t} \quad (7.1)$$

For the second scan:

$$-\left[\frac{dm}{dt}\right]_{i=1} = \frac{3m_0 + 10m_1 - 18m_2 + 6m_3 - m_4}{12\Delta t} \quad (7.2)$$

For the second to last scan:

$$-\left[\frac{dm}{dt}\right]_{i=n-1} = \frac{-3m_n - 10m_{n-1} + 18m_{n-2} - 6m_{n-3} + m_{n-4}}{12\Delta t} \quad (7.3)$$

For the last scan:

$$-\left[\frac{dm}{dt}\right]_{i=n} = \frac{-25m_n + 48m_{n-1} - 36m_{n-2} + 16m_{n-3} - 3m_{n-4}}{12\Delta t} \quad (7.4)$$

For any scans for which  $1 < i < n-1$  (where  $n$  is the endpoint of the test):

$$-\left[\frac{dm}{dt}\right]_i = \frac{-m_{i-2} + 8m_{n-1} - 8m_{i+1} + m_{i+2}}{12\Delta t} \quad (7.5)$$

The results of applying this algorithm to the mass curves for 25 mm PU Foam and PMMA specimens, and the mass curves of the B6S1 and C7S1 specimens can be seen in Figures 53-56.

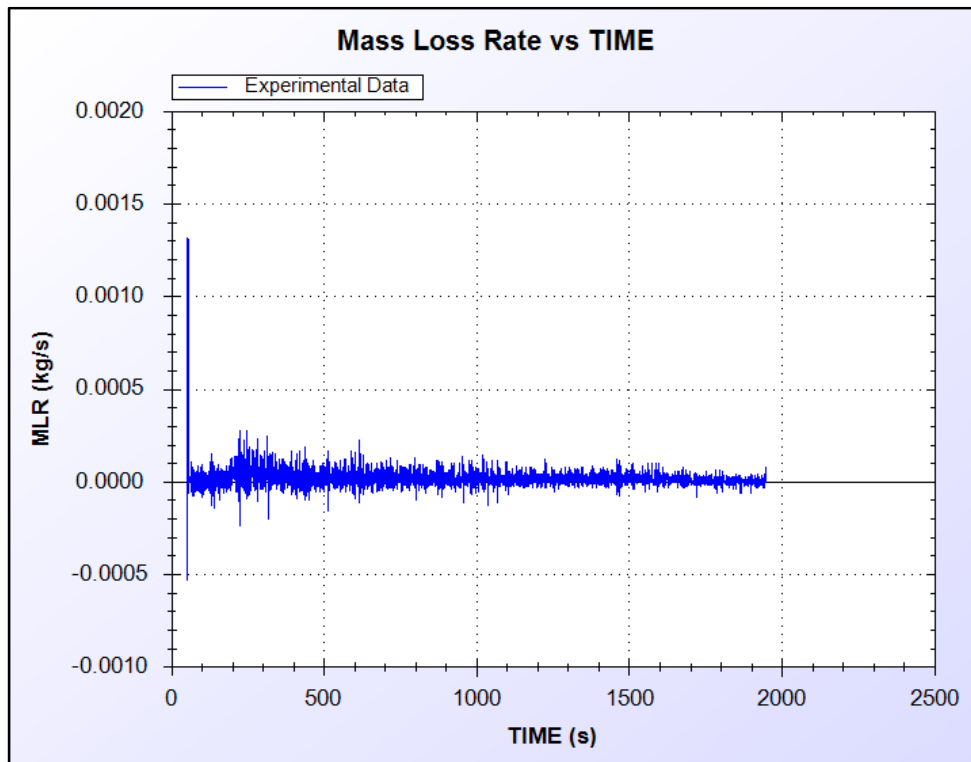


Figure 53: MDF (ASTM E 1354 MLR Algorithm)

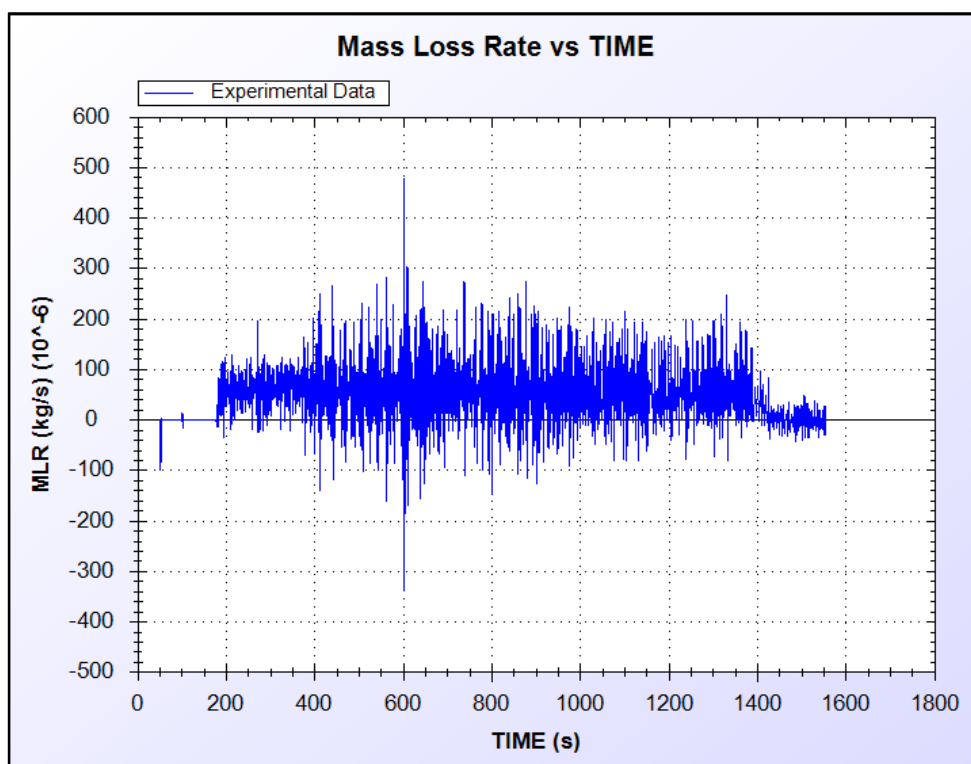


Figure 54: PMMA (ASTM E 1354 MLR Algorithm)

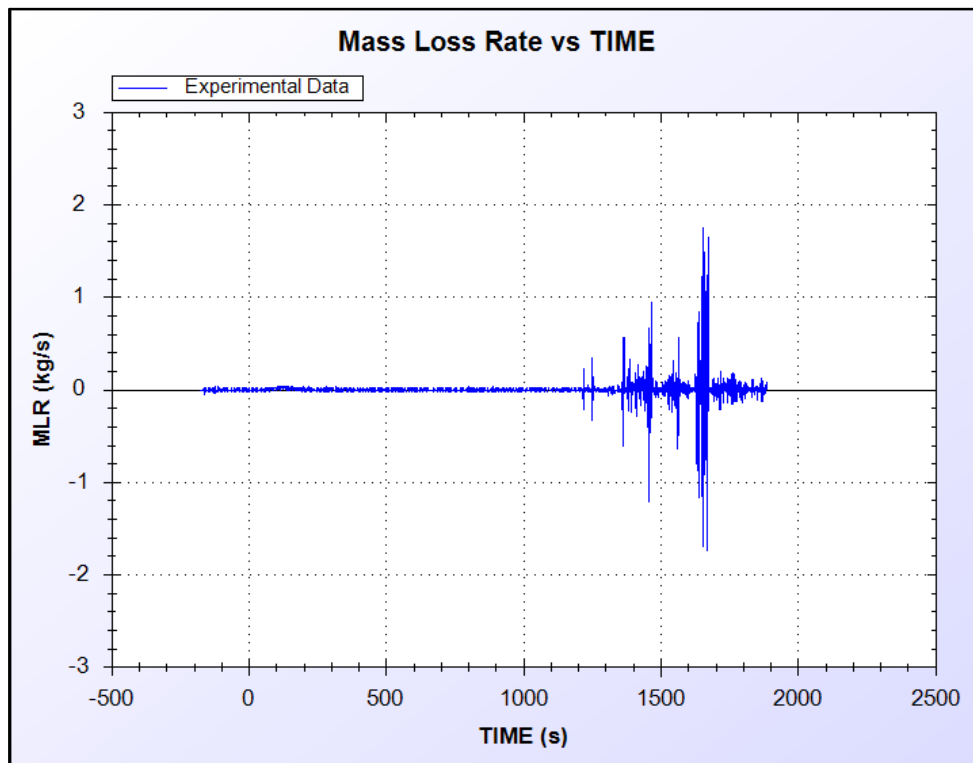


Figure 55: B6S1 (ASTM E 1354 MLR Algorithm)

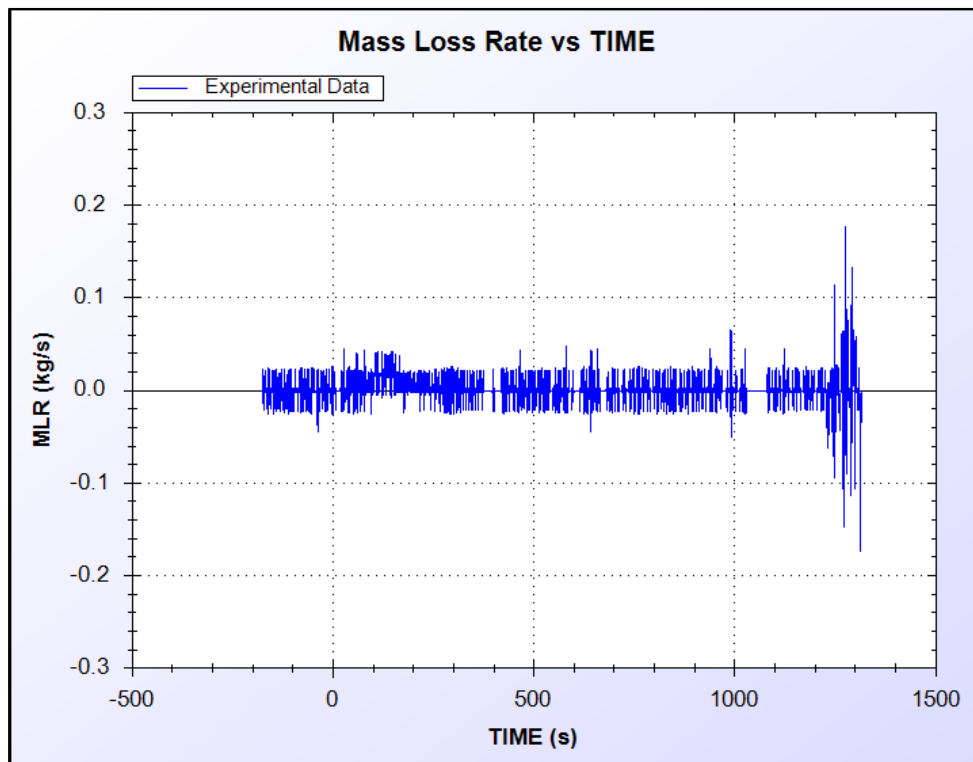


Figure 56: C7S1 (ASTM E 1354 MLR Algorithm)

None of the curves shown in Figures 53-56 show reasonable results; they all seem to exhibit large oscillations. Thus the *ASTM E 1354* MLR algorithm is not particularly suitable for reducing Cone Calorimeter or Furniture Calorimeter data.

Staggs [35] applied the Savitzky-Golay (SVG) algorithm to Cone Calorimeter mass data to obtain superior estimates of the Mass Loss Rate. The Savitzky-Golay algorithm fits an  $r^{th}$  order polynomial to a sliding windows of  $n_L + n_R + 1$  points of the original mass curve, differentiates this polynomial and then evaluates the resulting curve at the  $i^{th}$  point.

Thus the Mass Loss Rate at point  $k$  of the mass data is given in Equation 7.6.

$$\dot{m}_k = \frac{1}{t_{k+n_R} - t_{k-n_L}} \sum_{j=1}^r j p_j \tau_k^{j-1} \quad (7.6)$$

Where

$n_L$  = Number of points in the smoothing window to the left of the  $i^{th}$  mass data point.

$n_R$  = Number of points in the smoothing window to the right of the  $i^{th}$  mass data point.

$r$  = Order of the smoothing polynomial (Staggs recommended a value of 2).

$\tau_k$  = Transformed time values, calculated with Equation 7.7.

$$\tau_k = \frac{t_k - t_{i-n_L}}{t_{i+n_R} - t_{i-n_L}} \quad (7.7)$$

After trial and error it was found that a value of  $n_L = n_R = 20$  is a good starting point but this may be altered by the user at their discretion. Staggs [35] notes that the Mean Square Error (MSE) decreases as the value of  $n_L$  and  $n_R$  increases; but in reality these number should be kept as small as possible to prevent the loss of sudden peaks and troughs in the MLR curve whose lengths are less than  $n_L + n_R + 1$ . Staggs also notes that there is no point in increasing the value of  $r$  beyond 2 as the computed MLR noise is the least for this case. These parameters will be recorded in the *ReductionMethod* element of the *MLR TimeSeries* element.

The vector  $p$  of coefficient for the smoothing polynomial comes from the linear system presented in Equation 7.8.

$$Ap = b \quad (7.8)$$

Where

$$A_{jl} = \sum_{k=i-n_L}^{i+n_R} \tau_k^{l+j-2}, \quad j=1,2,\dots,r+1, \quad l=1,2,\dots,r+1 \quad (7.9)$$

$$b_j = \sum_{k=i-n_L}^{i+n_R} \tau_k^{j-1} m_k, \quad j=1,2,\dots,r+1 \quad (7.10)$$

Staggs then uses LU factorization to solve this linear system of equations with the following boundary conditions:

- As the index  $i$  approaches the end of the dataset  $n_R$  is reduced by one.
- At the start of the dataset additional points are introduced to the dataset since Staggs assumes that the mass is not changing. These additional points are defined by Equation 7.11.

$$t_i = t_1 + (i-1)(t_2 - t_1), m_i = m_1 \quad (7.11)$$

### **Modification to SVG MLR Algorithm:**

To simplify the second boundary condition if the mass is not changing at the start of the test and  $n_L + n_R + 1$  is much less than the total number of points within the experiment then the Mass Loss Rate maybe be set to zero for this region.

The matrix solution method LU factorization is switched to QR factorization to reduce sensitivity to rounding error i.e. matrix  $A$  can become highly singular depending on the experimental dataset involved.

## SVG Results:

The result of applying the SVG algorithm to the four mass curves can be seen in Figures 57-60.

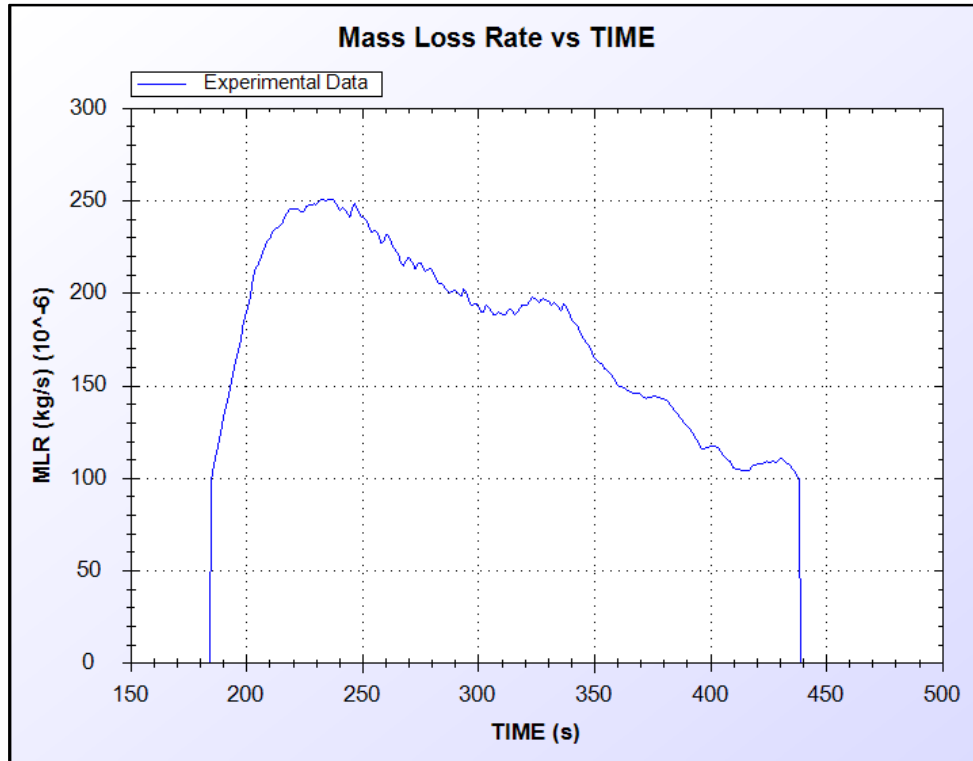


Figure 57: MDF (SVG MLR Algorithm)

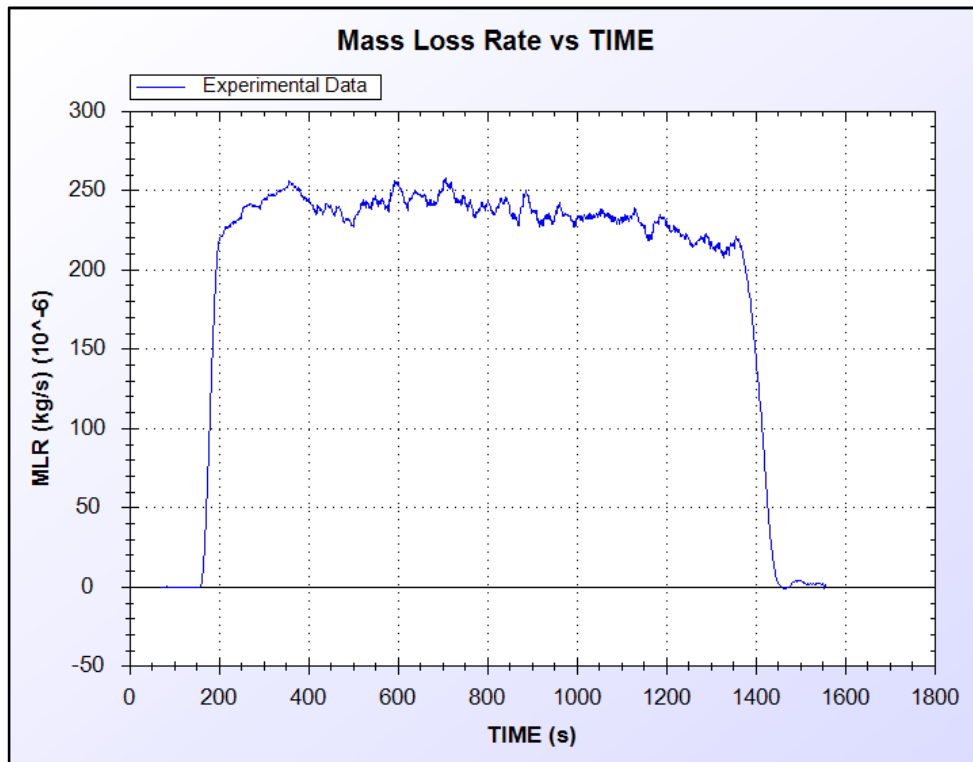
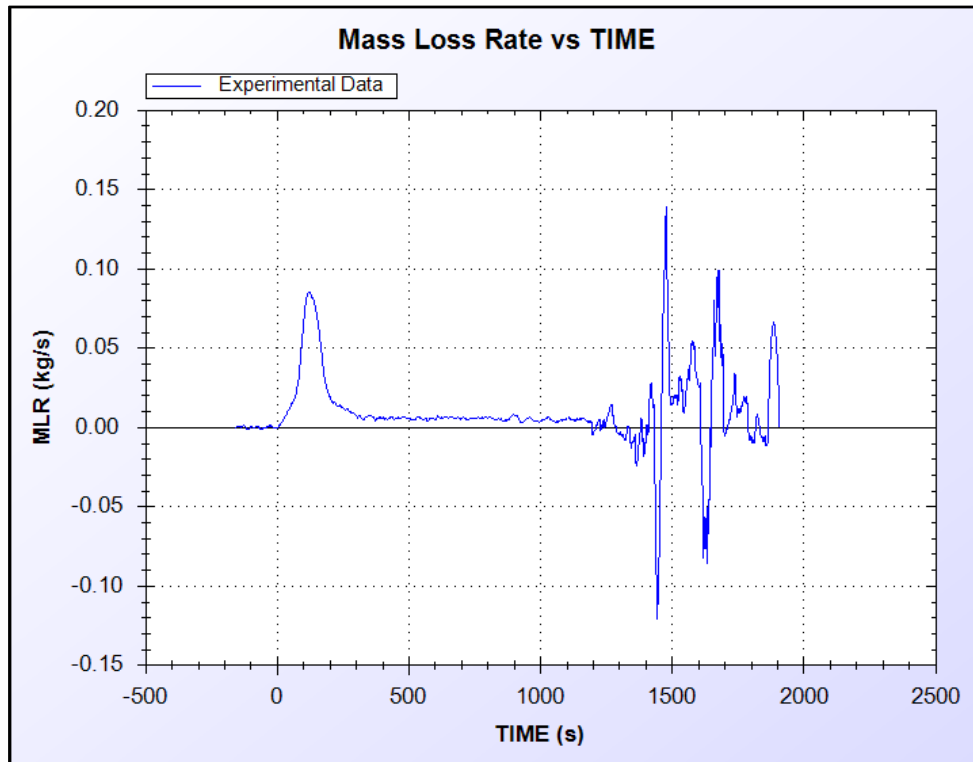
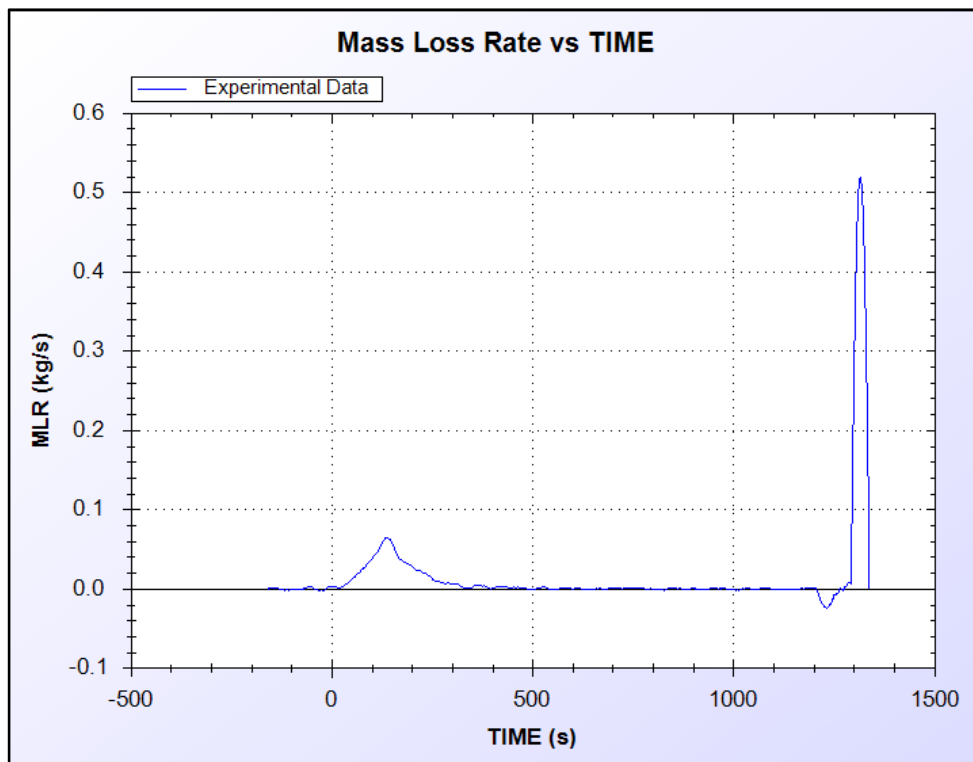


Figure 58: PMMA (SVG MLR Algorithm)



**Figure 59: B6S1 (SVG MLR Algorithm)**



**Figure 60: C7S1 (SVG MLR Algorithm)**



The SVG algorithm seems to perform well for the Cone Calorimeter tests but not for the upholstered furniture tests performed in the Furniture Calorimeter. It should be noted that Staggs had only apply this algorithm to Cone Calorimeter tests.

The spikes at the end of the furniture Calorimeter MLR curves coincide with the structural collapse of the upholstered chairs. These spikes are simply noise and while they are real; they are not due to burning. An algorithm to remove these unwanted events must be created to fulfill UCFIRE's goal of being able to semi autonomously reduce fire test data.

### **SVG's Correction Algorithm:**

To remove these unwanted events the main segment of the graphs must be identified with a start point and an end point, and any points outside of this range will be removed.

All MLR values below 5% (this value is arbitrary and can be changed by the user) of the maximum MLR or the threshold value (which are the number of decimal places that the mass are expressed to) are considered to be insignificant and will be set to zero. A typical resolution for mass measurements is 0.1g (1 significant figure) and if all the mass measurements were made to this resolution then the MLR cannot be expected to show an accuracy exceeding this value.

To identify this main segment the SVG correction algorithm starts by identifying the largest negative peak, and then finding the positive peak that occurs before the negative peak.

The last part of the algorithm involves starting at the peak MLR value and then traveling left until the MLR becomes zero after which all MLR values are set to zero. The process is then repeated for the right side of the curve. The correction algorithm can be seen in Figures 61 and 62 and the results of applying this Correction algorithm to the two furniture tests can be seen in Figures 63 and 64.

```

Function SVGCorrection(ByVal _mlr() As Double, ByVal tol As Double,
ByVal threshold As Double)

' Find the peak MLR value
Dim peak As Integer = 0
Dim negpeak As Integer = 0
Dim startpt As Integer = 0
Dim endpt As Integer = 0
Dim NEGMAX As Double = _mlr(0)
Dim MAX As Double = _mlr(0)

For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) < NEGMAX Then
        NEGMAX = _mlr(i)
        negpeak = i
    End If
Next

For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) > MAX And i < negpeak Then
        MAX = _mlr(i)
        peak = i
    End If
Next

' Calculate the tolerance level
Dim mlrtol As Double = (tol / 100) * MAX
For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) <= mlrtol Or _mlr(i) < threshold Then
        _mlr(i) = 0
    End If
Next

' Set all the values before and after the main set of data to zero.
For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) < 0 And i > peak Then
        endpt = i - 1
        Exit For
    End If

    If _mlr(i) = 0 And i > peak Then
        endpt = i
        Exit For
    End If
Next

For i As Integer = endpt To _mlr.Length - 1
    _mlr(i) = 0
Next

For i As Integer = _mlr.Length - 1 To 0 Step -1
    If _mlr(i) < 0 And i < peak Then
        startpt = i - 1
        Exit For
    End If

```

**Figure 61: SVG MLR Correction Code (Part 1)**

```

    If _mlr(i) = 0 And i < peak Then
        startpt = i
        Exit For
    End If
Next

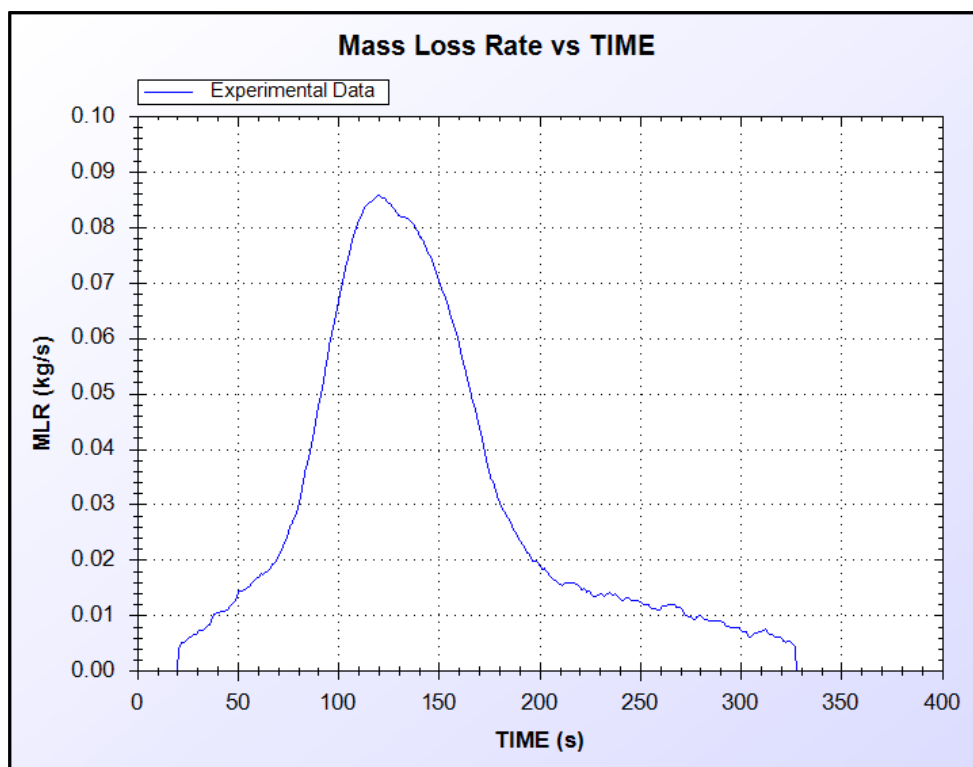
For i As Integer = 0 To startpt
    _mlr(i) = 0
Next

Return _mlr

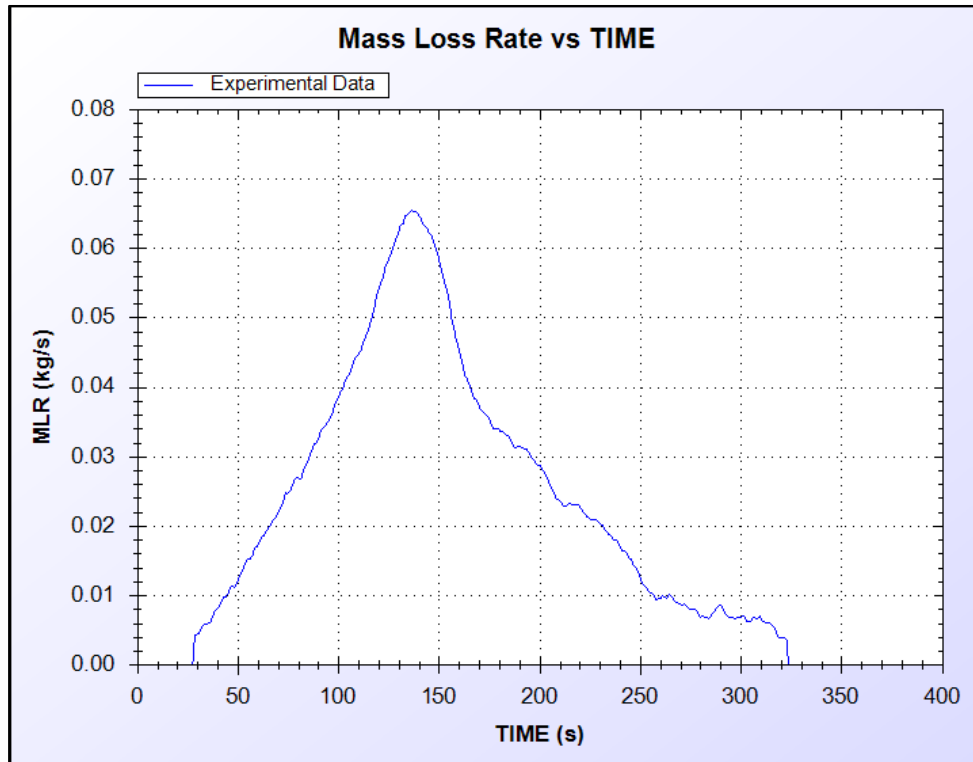
End Function

```

**Figure 62: SVG MLR Correction Code (Part 2)**



**Figure 63: Corrected MLR Curve for B6S1**



**Figure 64: Corrected MLR Curve for C7S1**

These two new curves seem much more reasonable but if the oscillations began with a positive peak before the largest negative peak, then this algorithm would fail.

The improved SVG MLR correction algorithm involves finding the longest section that the MLR is non-zero; this will be the main section of the MLR. The algorithm involves starting at the peak MLR value and then traveling left, and then right until the MLR becomes zero. All values after or before this point respectively are then set to zero.

The correction algorithm can be seen in Figures 65 and 66 and the results of applying this improved correction algorithm to all four tests can be seen in Figures 67-70.

```

Function ImprovedSVGCorrection(ByVal _mlr() As Double, ByVal tol As Double, ByVal threshold As Double)

' Find the longest section of positive MLR values. This is the main segment.
Dim startpt As Integer = 0
Dim endpt As Integer = 0
Dim maxdt As Integer = 0
Dim dt As Integer = 0

For i As Integer = 0 To _mlr.Length - 1
    dt = 0
    Dim k As Integer = i
    While _mlr(k) > 0 And k < _mlr.Length - 1
        dt = dt + 1
        k = k + 1
    End While
    If dt > maxdt Then
        maxdt = dt
        startpt = i
        endpt = i + maxdt
    End If
Next

For i As Integer = 0 To startpt
    _mlr(i) = 0
Next

For i As Integer = endpt To _mlr.Length - 1
    _mlr(i) = 0
Next

' Find the peak value and use this to remove insignificant values.
Dim peak As Integer = 0
Dim MAX As Double = _mlr(0)

For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) > MAX Then
        MAX = _mlr(i)
        peak = i
    End If
Next

Dim mlrtol As Double = (tol / 100) * MAX
For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) < mlrtol Or _mlr(i) < threshold Then
        _mlr(i) = 0
    End If
Next

' Set all the values before the main set of data to zero.
For i As Integer = _mlr.Length - 1 To 0 Step -1
    If _mlr(i) < 0 And i < peak Then
        startpt = i - 1
        Exit For
    End If

```

**Figure 65: Improved SVG MLR Correction Algorithm (Part1)**

```

    If _mlr(i) = 0 And i < peak Then
        startpt = i
        Exit For
    End If
Next

For i As Integer = 0 To startpt
    _mlr(i) = 0
Next

' Set all the values after the main set of data to zero.
For i As Integer = 0 To _mlr.Length - 1
    If _mlr(i) < 0 And i > peak Then
        endpt = i - 1
        Exit For
    End If
If _mlr(i) = 0 And i > peak Then
    endpt = i
    Exit For
End If
Next

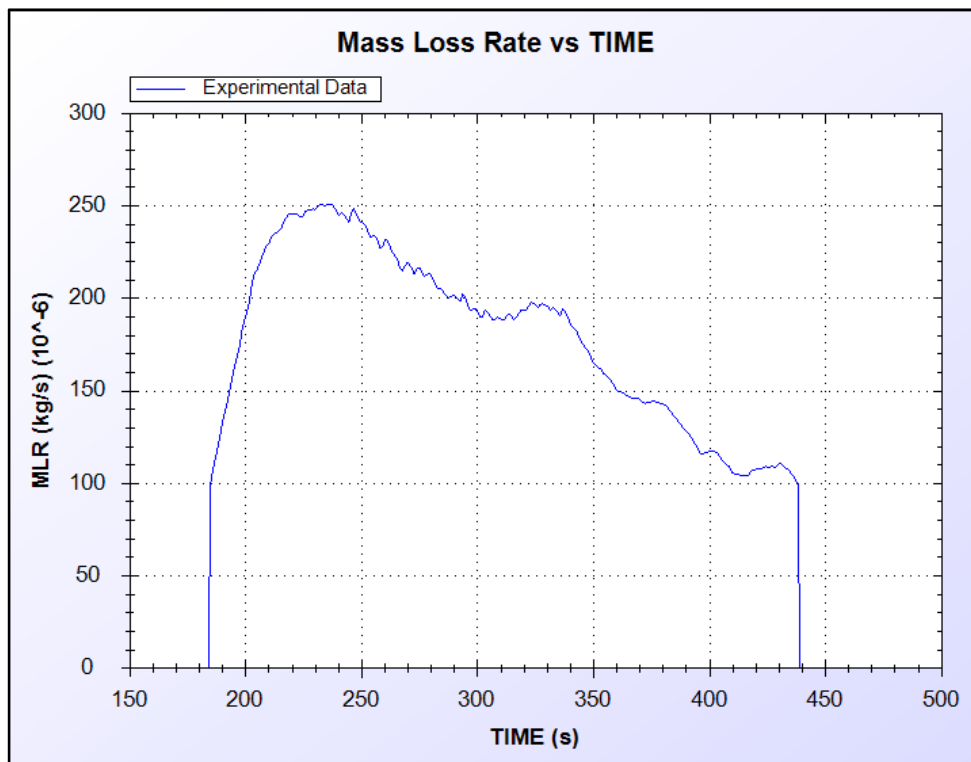
For i As Integer = endpt To _mlr.Length - 1
    _mlr(i) = 0
Next

Return _mlr

End Function

```

**Figure 66: Improved SVG MLR Correction Algorithm (Part 2)**



**Figure 67: MDF (Improved SVG MLR Algorithm)**

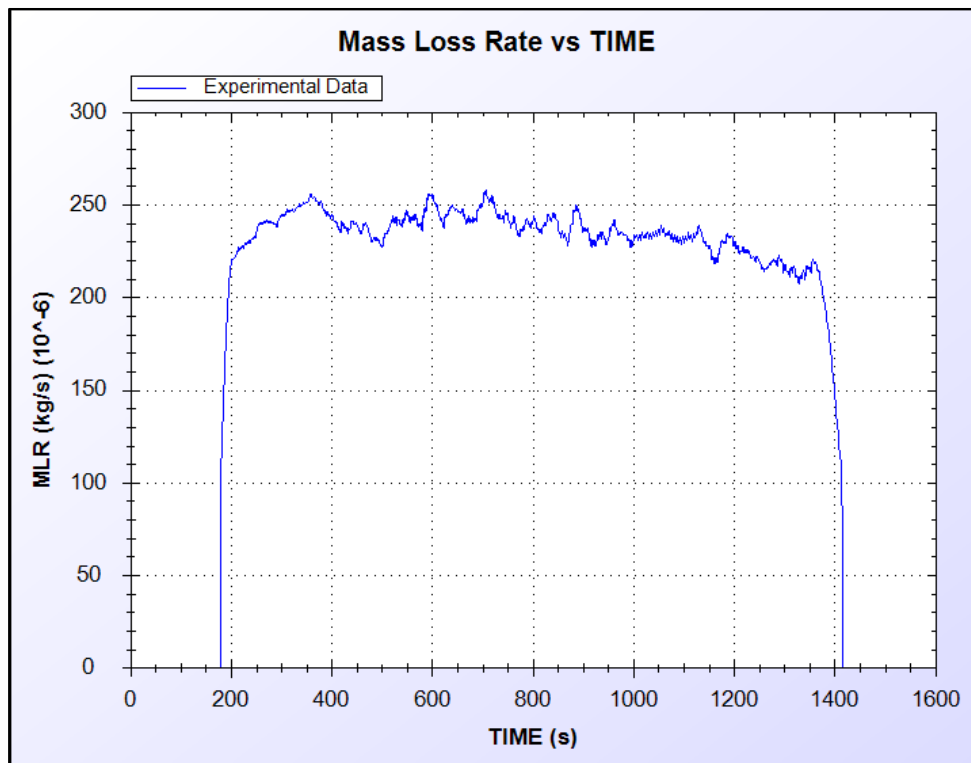


Figure 68: PMMA (Improved SVG MLR Algorithm)

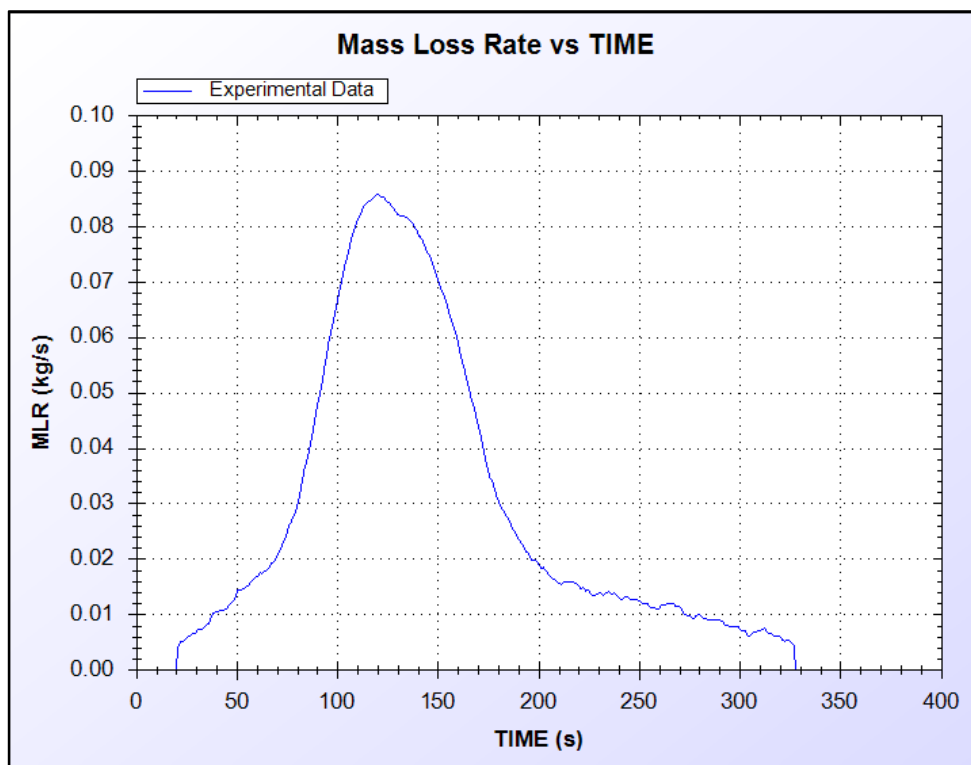
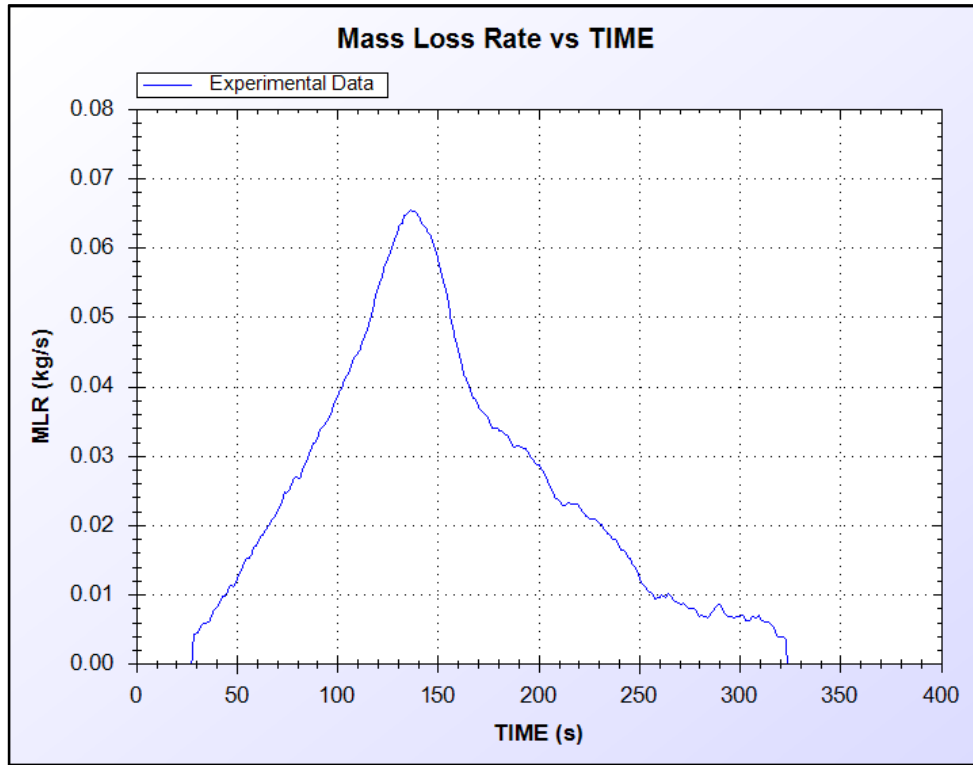


Figure 69: B6S1 (Improved SVG MLR Algorithm)



**Figure 70: C7S1 (Improved SVG MLR Algorithm)**

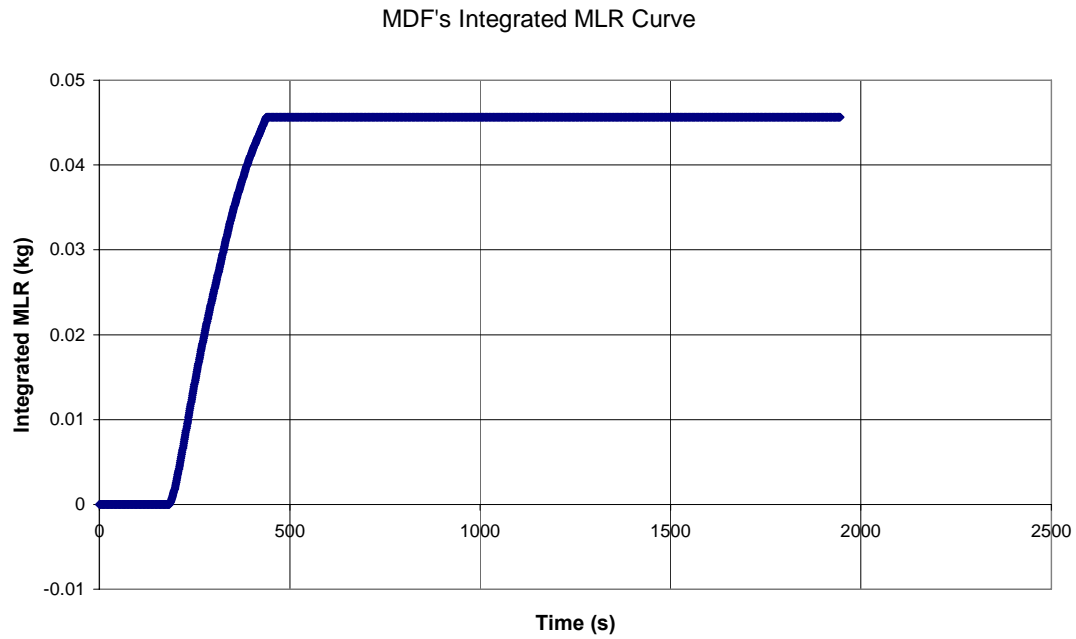
### **Validation of the Corrected SVG MLR Algorithm**

Numerical integration was used to determine the area under each MLR curve, and this can be compared with the original mass curves. If the corrected SVG MLR algorithm is indeed accurate there should be no significant discrepancy between the two curves. Assuming that the time step is small compared to the total number of steps (which is true for all four cases examined); the integrated curve can be approximated with the following Riemann sum [36] shown in Equation 7.12.

$$\int_a^b HRR(t)dt \approx \sum_{k=1}^n HRR(t_k^*)\Delta t_k \quad (7.12)$$

The integrated MLR curve for the MDF specimen can be seen in Figure 71.

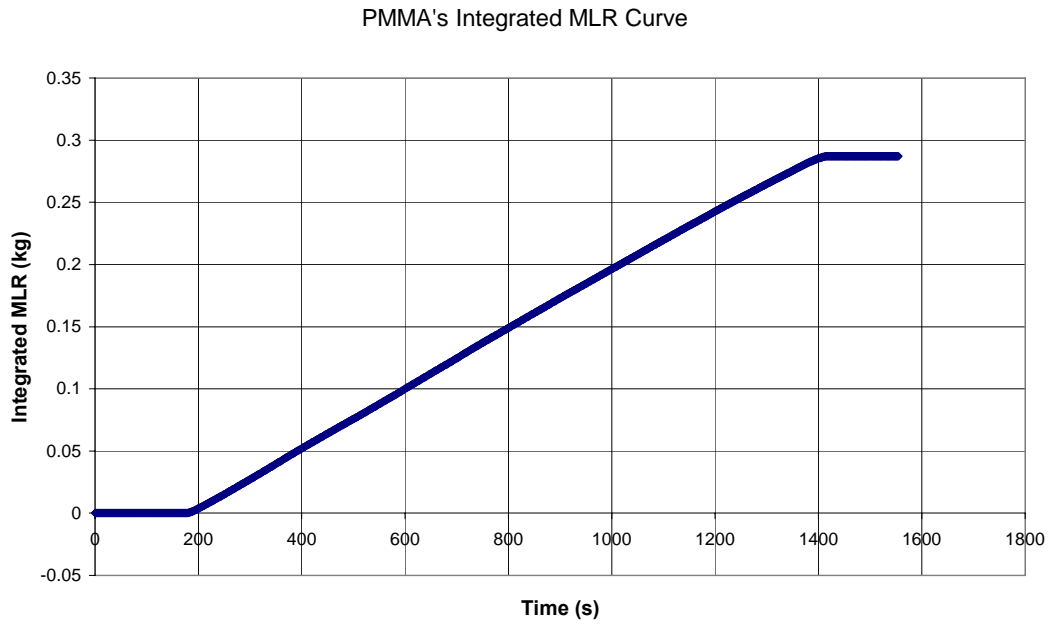




**Figure 71: Integrated Mass Curve for MDF**

The integrated MLR curve for the MDF specimen starts at 184.9 s and ends at 438 s; the area under this curve was found to be 0.0456 kg. At 184.9 s the original mass curve starts at 0.1867 kg and drops to 0.1412 kg at 438 s. This is a total change of 0.0455 kg. Thus the discrepancy between the integrated MLR curve and the mass curve for the MDF specimen is less than 0.1 g indicating that this MLR algorithm is valid.

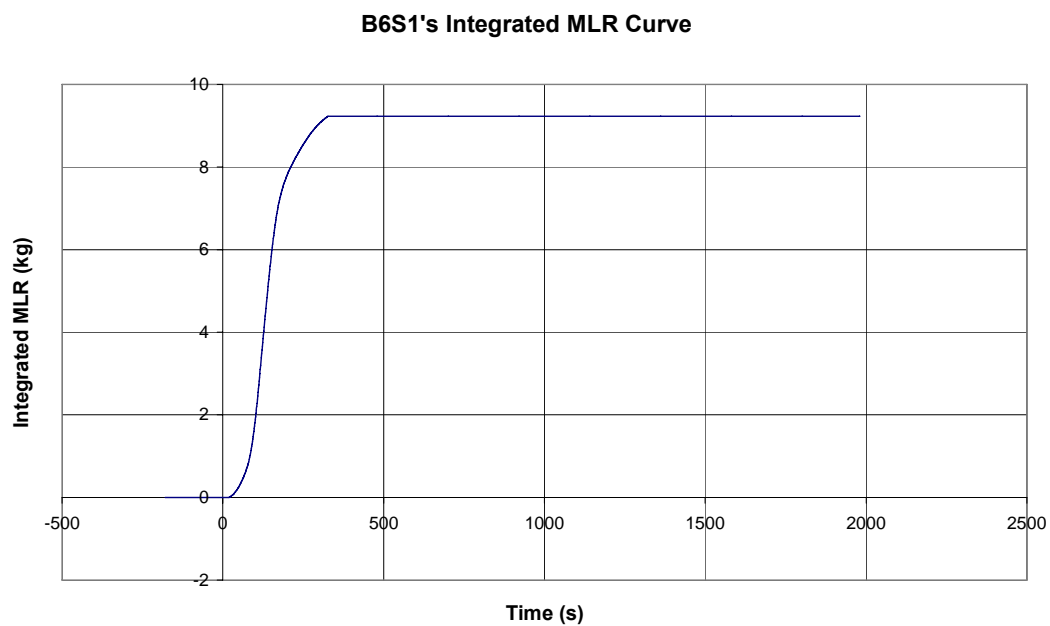
The integrated MLR curve for the PMMA specimen can be seen in Figure 72.



**Figure 72: Integrated Mass Curve for PMMA**

The integrated MLR curve for the PMMA specimen starts at 178.7 s and ends at 1413.5 s; the area under this curve was found to be 0.287 kg. At 178.7 s the original mass curve starts at 0.291 kg and drops to 0.00300 kg at 1413.5 s. This is a total change of 0.288 kg. Thus the discrepancy between the integrated MLR curve and the mass curve for the PMMA specimen is less than 0.1 g indicating that this MLR algorithm is valid.

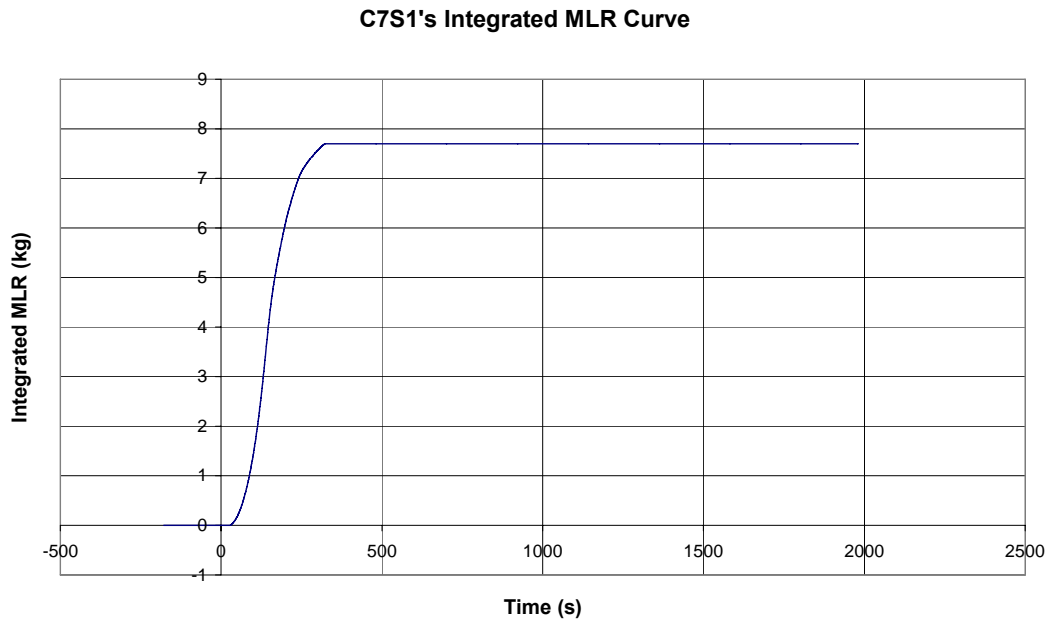
The integrated MLR curve for B6S1 can be seen in Figure 73.



**Figure 73: Integrated Mass Curve for B6S1**

The integrated MLR curve for B6S1 starts at 20.6 s and ends at 326.5 s; the area under this curve was found to be 9.30 kg. At 20.6 s the original mass curve starts at 21.25 kg and drops to 12.01 kg at 326.5 s. This is a total change of 9.24 kg. Thus the discrepancy between the integrated MLR curve and the mass curve for B6S1 is less than 0.1 kg indicating that this MLR algorithm is valid.

The integrated MLR curve for C7S1 can be seen in Figure 74.



**Figure 74: Integrated Mass Curve for C7S1**

The integrated MLR curve for C7S1 starts at 28.4 s and ends at 322.4 s; the area under this curve was found to be 7.7 kg. At 28.4 s the original mass curve starts at 23.4 kg and drops to 15.68 kg at 322.4 s. This is a total change of 7.72 kg. Thus the discrepancy between the integrated MLR curve and the mass curve for C7S1 is less than 0.1 kg indicating that this MLR algorithm is valid.

### 7.3.2 Heat of Combustion

The effective Heat of Combustion is the heat energy released when one unit of mass of a substance undergoes combustion. This parameter was found by dividing the HRR data by the MLR data (Equation 7.13).

$$HC = \frac{HRR}{MLR} \quad (7.13)$$

The signal is then smoothed with the basic Savitzky-Golay filter. The Savitzky-Golay filter's settings are the same as those used for the Mass Loss Rate except now the smoothing polynomial will not be differentiated. The SVG filter could be equally be applied to only the HRR values before calculating HC but this may possibly result in a noiser HC curve.

The results of this algorithm can be seen in Figures 75-78.

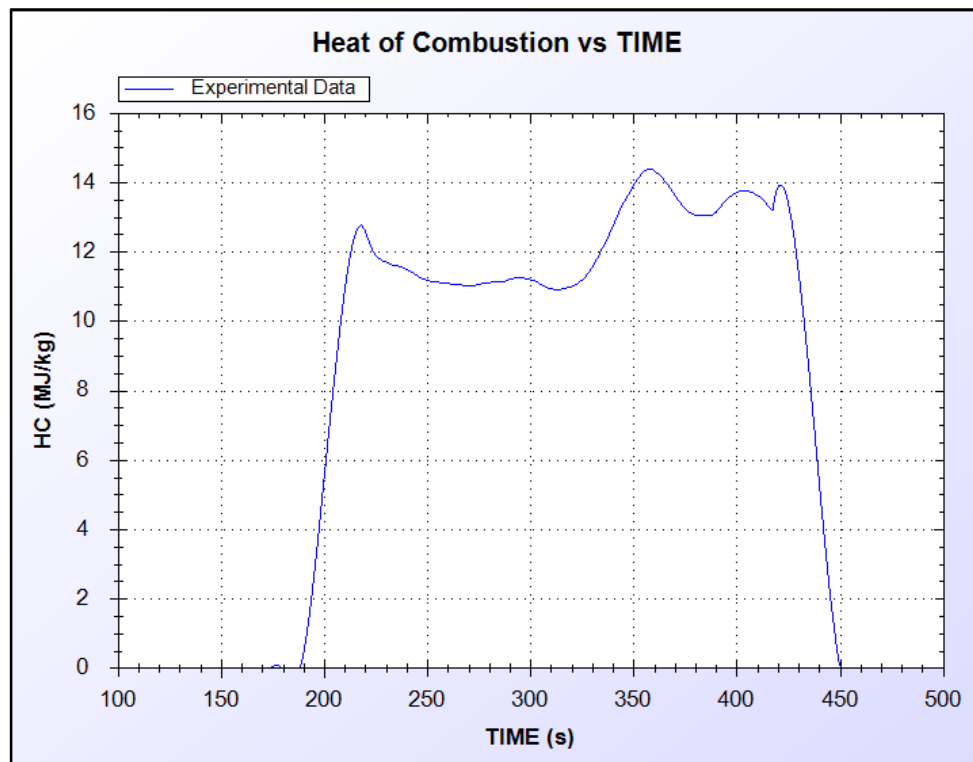
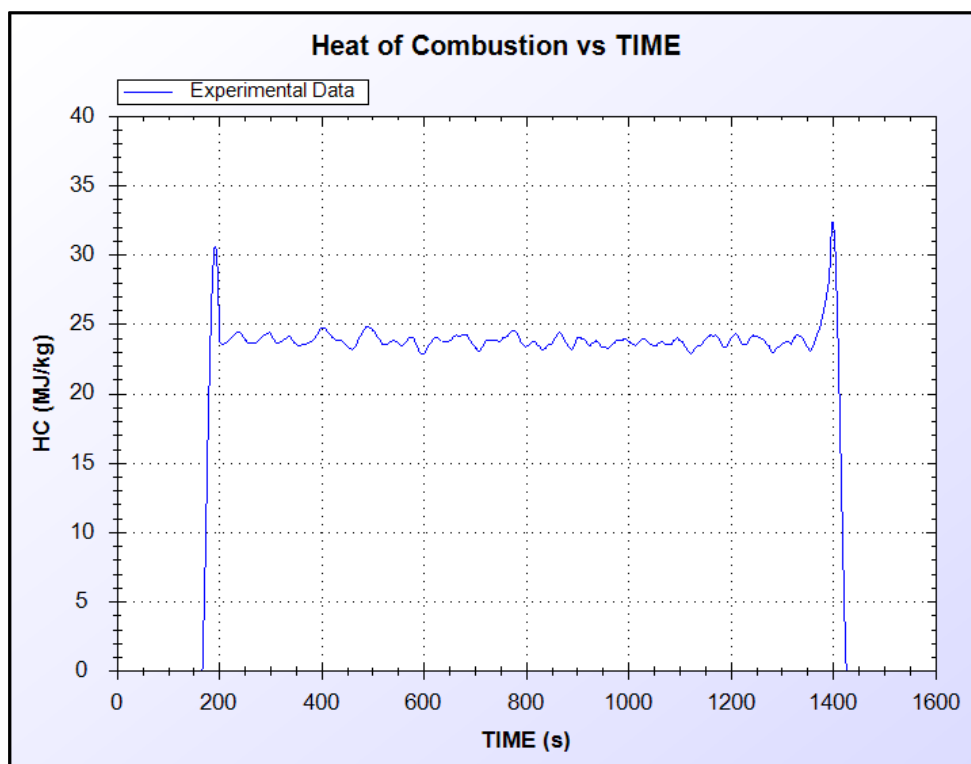


Figure 75: HC Curve for MDF

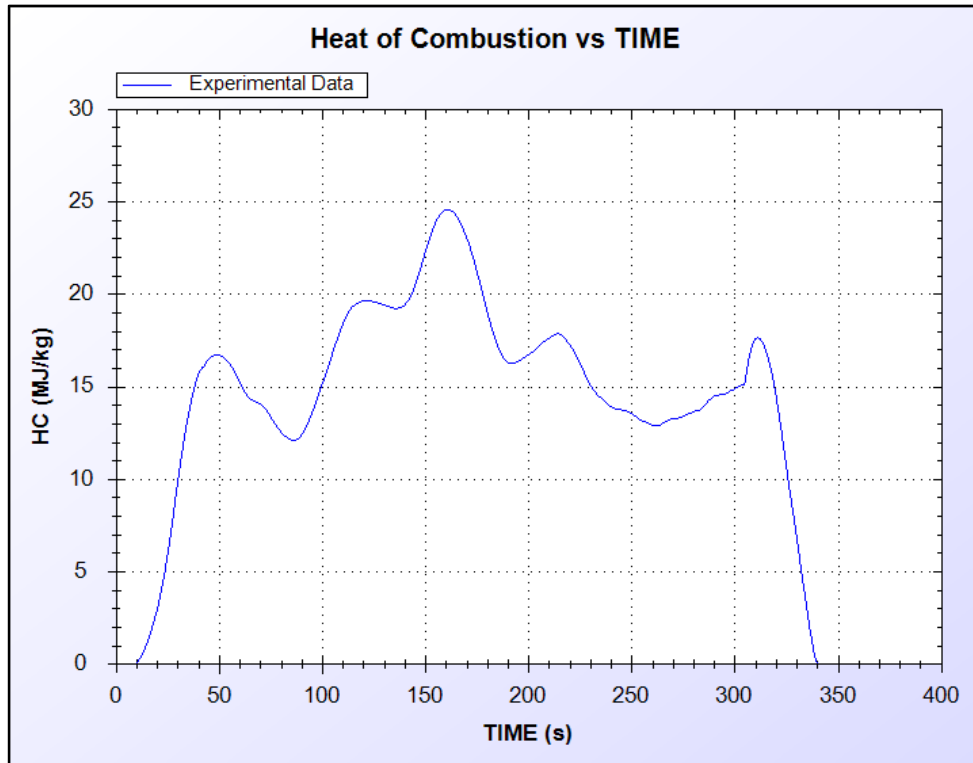
The peak and average Heat of Combustion for the MDF specimen was calculated to be 14.4 MJ/kg and 11.1 MJ/kg respectively. The average value compares well with

the average HC value calculated by Pau [30] of 12.9 MJ/kg which he calculated between ignition (188 s) and the end of the test (1945.8 s).



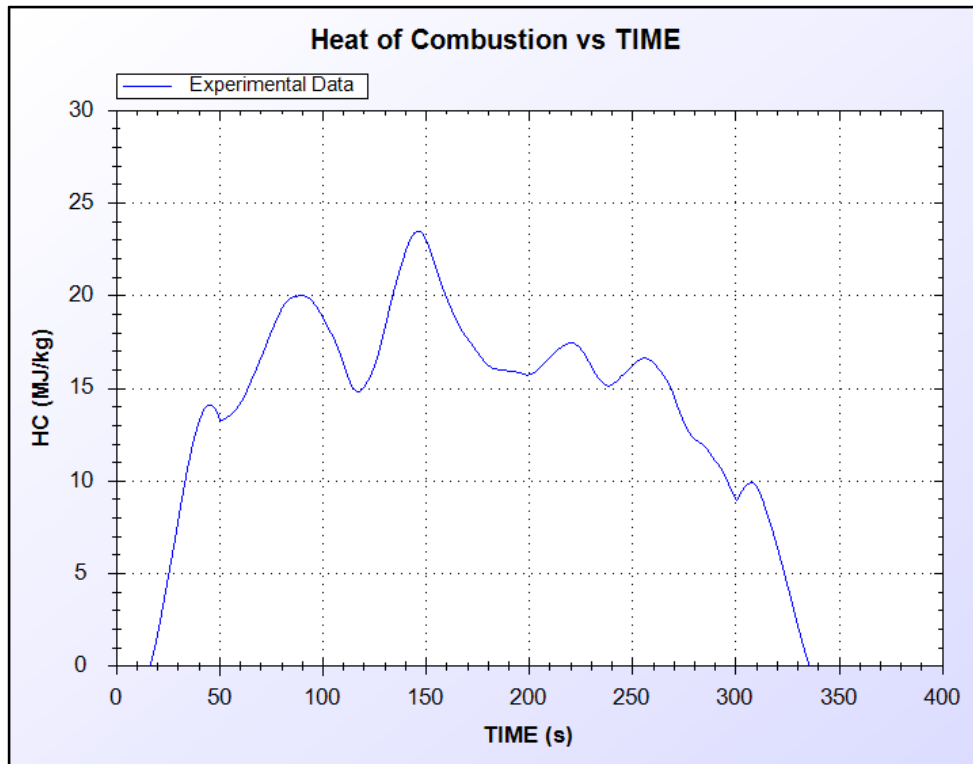
**Figure 76: HC Curve for PMMA**

The peak and average Heat of Combustion for the PMMA specimen was calculated to be 32.4 MJ/kg and 23.6 MJ/kg respectively. The average value compares well with the value calculated by Pau [30] of 23.4 MJ/kg which he calculated between ignition (128.5 s) and the end of the test (1554.6 s).



**Figure 77: HC Curve for B6S1**

The peak and average Heat of Combustion for B6S1 was calculated to be 24.6 MJ/kg and 15.1 MJ/kg respectively. Hill [31] did not compute the average heat of combustion for his experiments.



**Figure 78: HC Curve for C7S1**

The peak and average Heat of Combustion for C7S1 was calculated to be 23.5 MJ/kg and 14.6 MJ/kg respectively. Hill [31] did not compute the average heat of combustion for his experiments.

### 7.3.3 Total Heat Released

The total heat released (HRRTOT) is simply the area under the heat release rate curve. This can also be calculated with the Riemann sum [36] shown again in Equation 7.14.

$$\int_a^b HRR(t)dt \approx \sum_{k=1}^n HRR(t_k^*)\Delta t_k \quad (7.14)$$

The Total Heat Released per Unit Area (HRRTOTPUA) can be found for Cone Calorimeter tests by dividing the HRRTOT data by the specified nominal exposed surface area.

The total heat released per unit area for the MDF specimen can be seen in Figure 79.

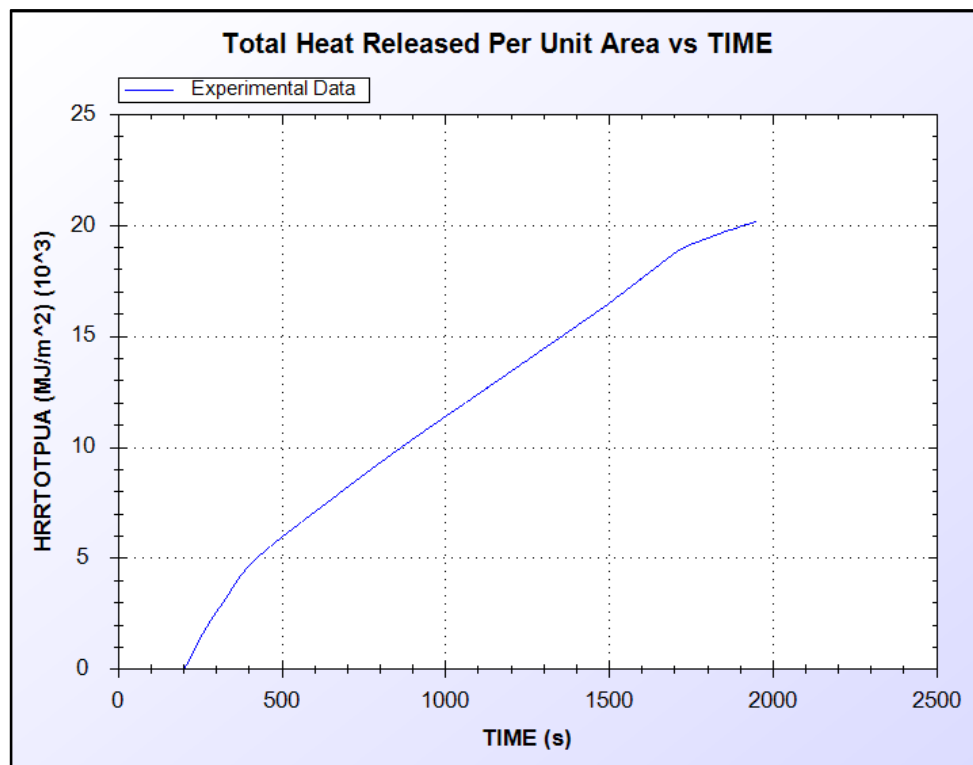


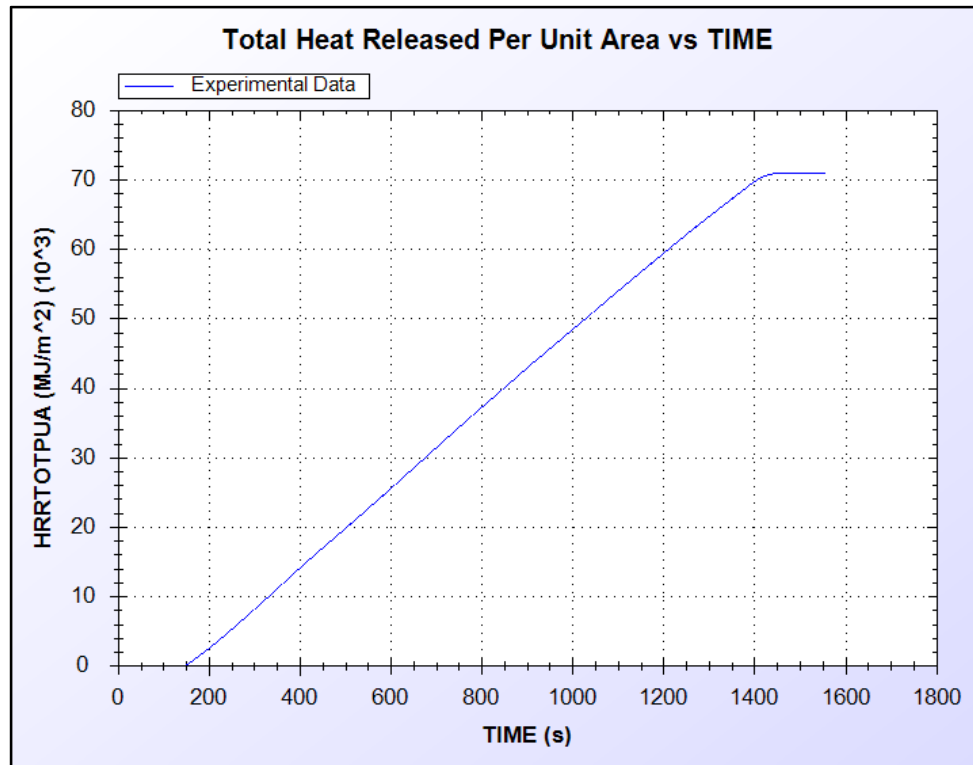
Figure 79: HRRTOTPUA Curve for MDF

The total heat released per unit area was 20,200 MJ/m<sup>2</sup>, or equivalently 202 MJ. The average value compares well with the HRRTOT value calculated by Pau [30] of 192



MJ/m<sup>2</sup> which he calculated after the last negative value of HRRPUA (144.1 s) and the end of the test (1945.8 s).

The total heat released per unit area for the PMMA specimen can be seen in Figure 80.



**Figure 80: HRRTOTPUA Curve for PMMA**

The total heat released per unit area was 70,900 MJ/m<sup>2</sup>, or equivalently 709 MJ. The average value compares well with the HRRTOT value calculated by Pau [30] of 678 MJ/m<sup>2</sup> which he calculated after the last negative value of HRRPUA (110.7 s) and the end of the test (1945.8 s).

The total heat released for chair B6S1 can be seen in Figure 81.

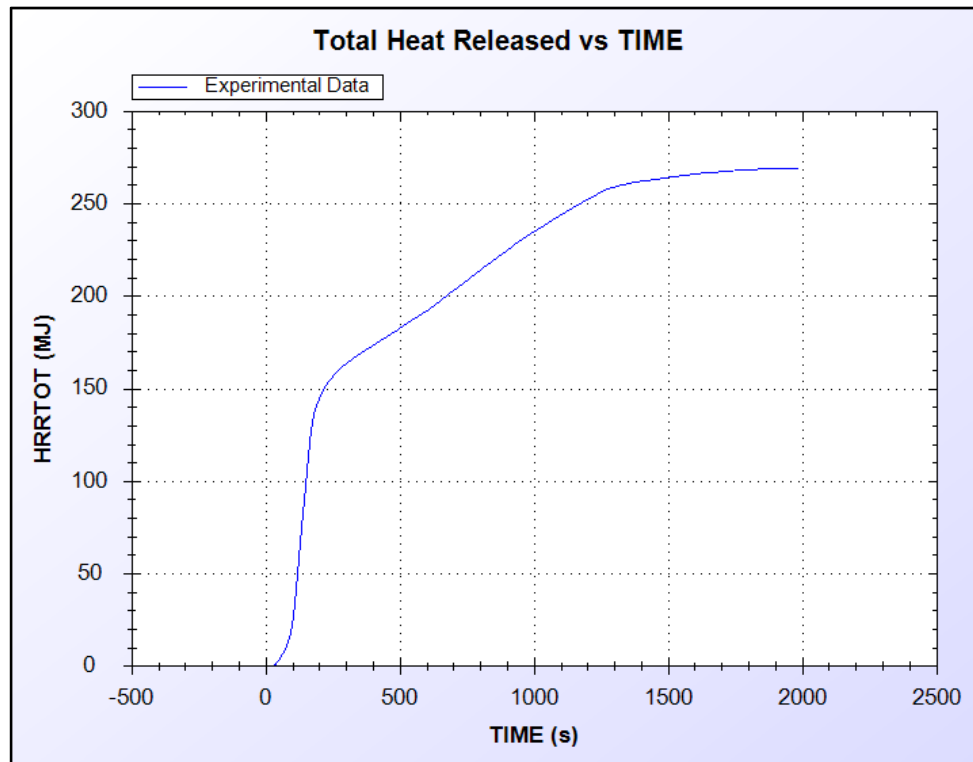


Figure 81: HRRTOT Curve for B6S1

The total heat released for chair C7S1 can be seen in Figure 82.

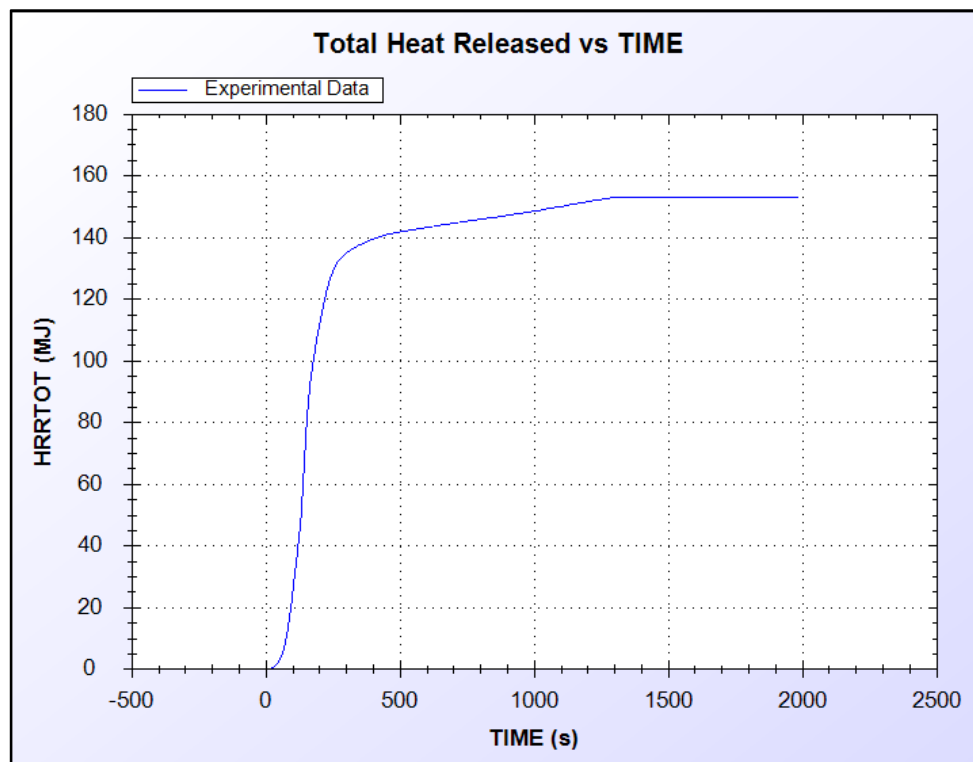


Figure 82: HRRTOT Curve for C7S1

### 7.3.4 Total Smoke Released

The Total Smoke Released (TSR) can be calculated in a similar fashion to how the Total Heat Released was calculated except the Rate of Smoke Released (RSR) data will be used in place of the HRR data. The Rate of Smoke Released is not required by the Cone Calorimeter Standard *ASTM E 1353-02* so Pau [30] did not measure this quantity, however the RSR is required by the Furniture Standard (*ASTM E 1537*) but Hill did not measure this quantity. However this algorithm is exactly the same as the algorithm to calculate the Total Heat Released, it just uses RSR instead of HRR values, so it is therefore not necessary to perform this algorithm on exemplar data to prove its efficacy.

### 7.3.5 Gas Yields

The gas yields were measured with Equation 7.15.

$$f_x = \frac{\dot{m}_{DUCT} \times \chi_x \times \frac{M_x}{M}}{MLR} \quad (7.15)$$

Where

$f_x$  = Yield of species  $x$ .

$\dot{m}_{DUCT}$  = Mass flow through the duct (kg/s).

$\chi_x$  = Mole fraction of species  $x$  (-).

$M_x$  = Molecular weight of gas species  $x$  (kg/kmol).

$M$  = Molecular weight of incoming and exhaust air (29 kg/kmol).

Where  $M_x$  values are shown in Table 16.

Gas	Molecular Weight (kg/kmol)
Carbon Monoxide	28
Carbon Dioxide	44
Water Vapour	18
Hydrogen Bromide	81
Hydrogen Chloride	36
Hydrogen Cyanide	27

Table 16: Molecular Weights for Common Fire Gases

The yield of CO<sub>2</sub> for MDF can be seen in Figure 83.

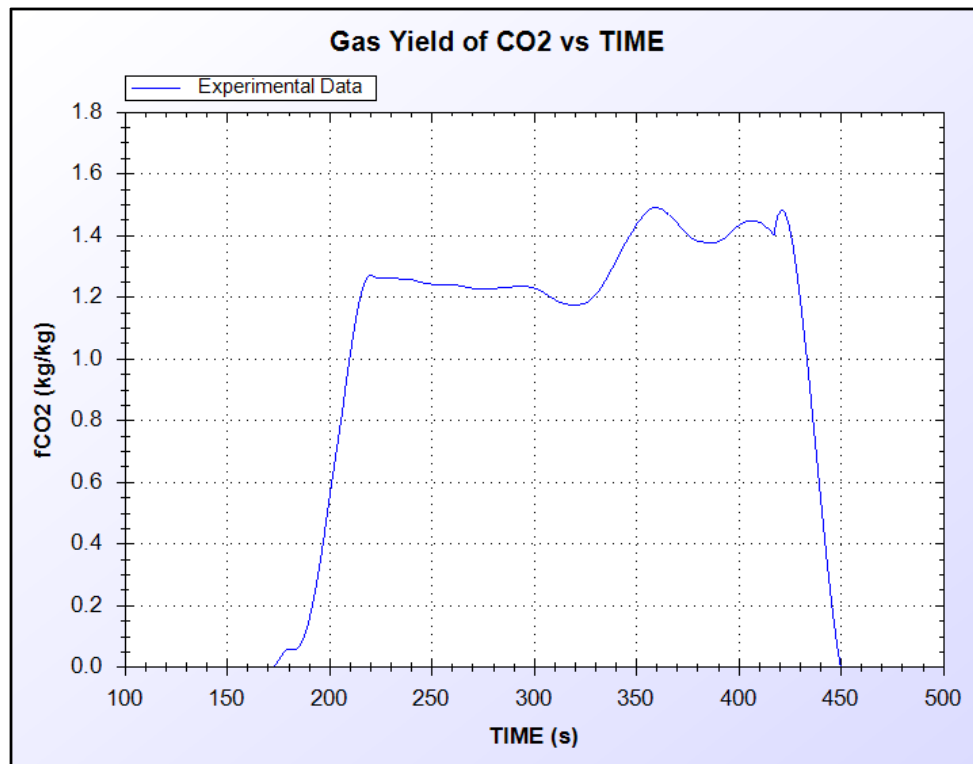
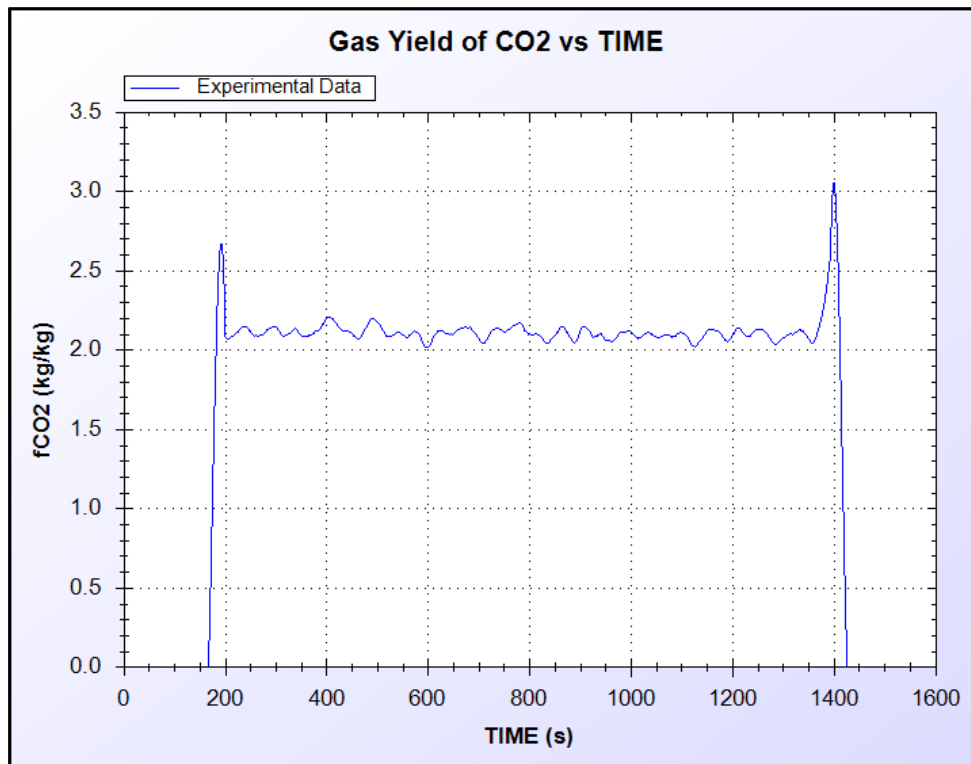


Figure 83: CO<sub>2</sub> Yield for MDF

The peak and average yield of CO<sub>2</sub> for the MDF specimen was calculated to be 1.49 kg/kg and 1.11 kg/kg respectively. The yield of CO<sub>2</sub> from the *SFPE Handbook of Fire Protection Engineering* [37] for MDF is 1.2 kg/kg which is within the range of the average and the maximum value calculated by UCFIRE.

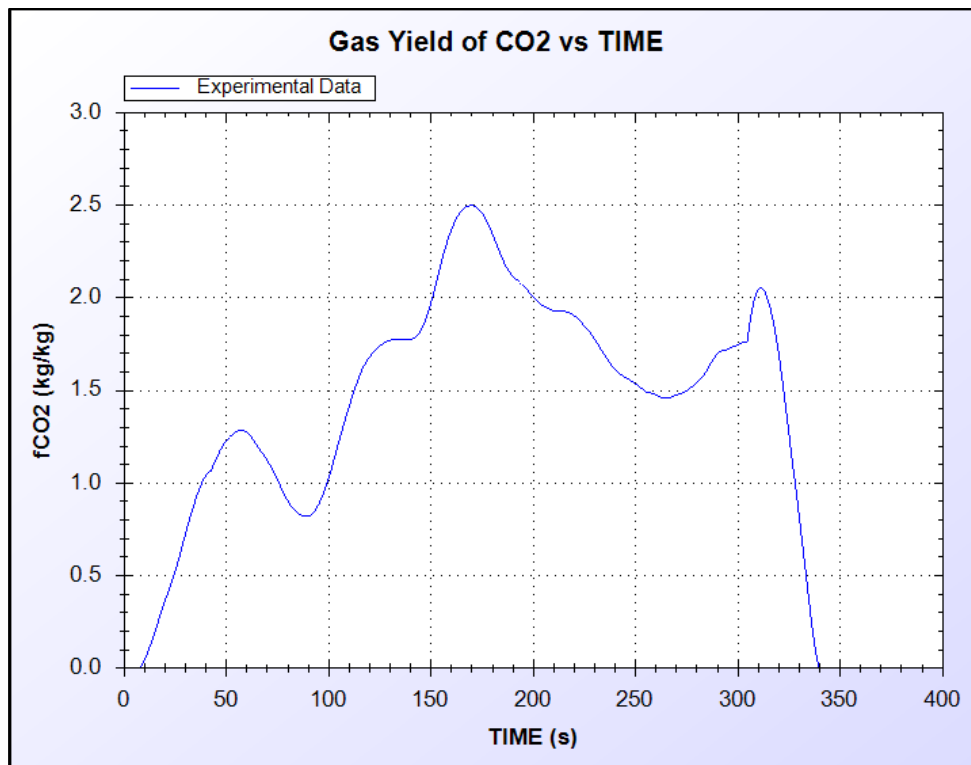
The yield of CO<sub>2</sub> for PMMA can be seen in Figure 84.



**Figure 84: CO<sub>2</sub> Yield for PMMA**

The peak and average yield of CO<sub>2</sub> for the PMMA specimen was calculated to be 3.06 kg/kg and 2.10 kg/kg respectively. The yield of CO<sub>2</sub> from the *SFPE Handbook of Fire Protection Engineering* [37] for PMMA is 2.12 kg/kg which is very close to the average value calculated by UCFIRE.

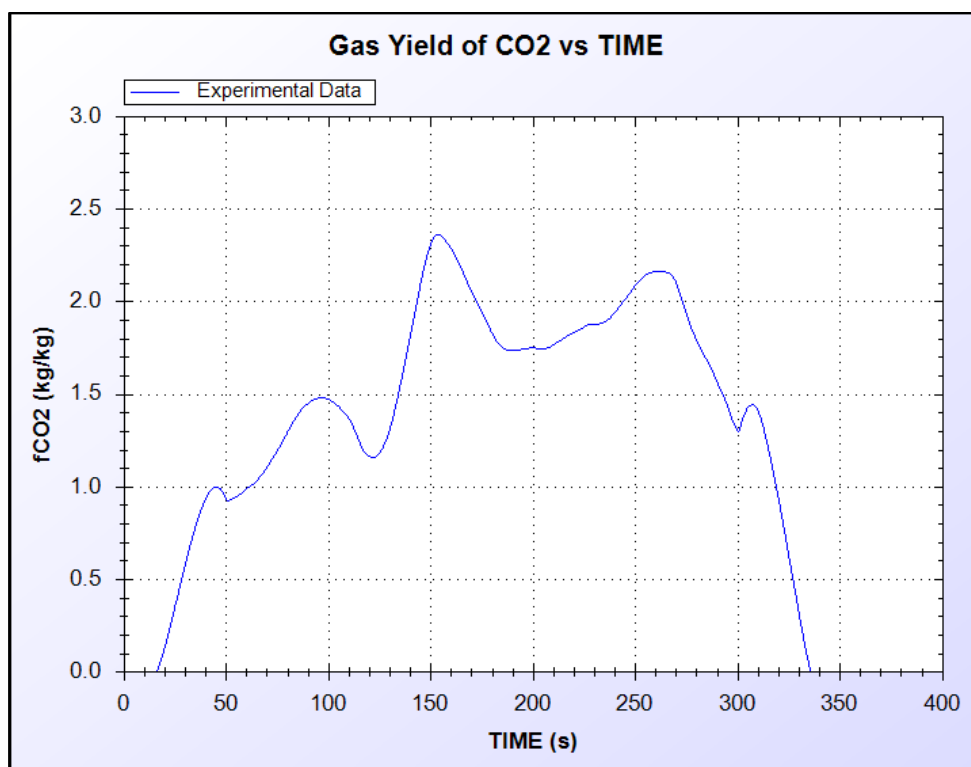
The yield of CO<sub>2</sub> for B6S1 can be seen in Figure 85.



**Figure 85: CO<sub>2</sub> Yield for B6S1**

The peak and average yield of CO<sub>2</sub> for chair B6S1 was calculated to be 2.50 kg/kg and 1.50 kg/kg respectively. Hill [31] did not calculate gas yields for his experiments.

The yield of CO<sub>2</sub> for C7S1 can be seen in Figure 86.



**Figure 86: CO<sub>2</sub> Yield for C7S1**

The peak and average yield of CO<sub>2</sub> was calculated to be 2.36 kg/kg and 1.49 kg/kg respectively. Hill [31] did not calculate gas yields for his experiments.

Note that the gas yield of nitrous oxides (NO<sub>x</sub>) and soot cannot be calculated using this method since the molecular mass of NO<sub>x</sub> and soot are unknown. The yield of soot however may be calculated with the method to be presented in the next section.

### 7.3.5 Smoke Yield

Mulholland, Johnson, Fernandez and Shear [38] developed and tested a new smoke concentration meter based on light-extinction measurements made with a Helium-Neon laser.

Using their method the yield of smoke may be calculated from Equation 7.16:

$$\varepsilon = \frac{C_s \dot{V} K}{\sigma_s \dot{m}_f} \quad (7.16)$$

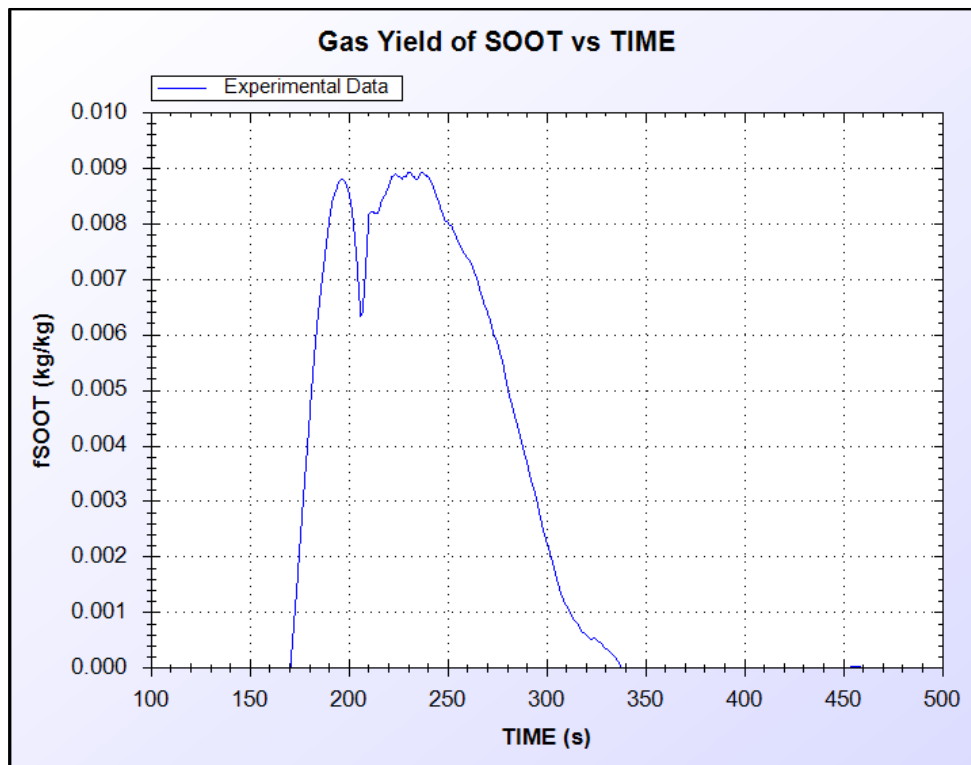
Where

- $\varepsilon$  = The yield of smoke (kg/kg).
- $C_s$  = Smoke profile factor (Mulholland et al. takes this to be 0.97).
- $\dot{V}$  = The exhaust flow rate (either as a scalar from *TESTPARAMETERS* or it can be specified as a *TIMESERIES*). The time series values of the exhaust flow rate will be chosen in preference to the scalar value.
- $K$  = The extinction coefficient (-).
- $\sigma_s$  = The specific extinction area (taken to be 8.7 m<sup>2</sup>/g).
- $\dot{m}_f$  = The mass loss rate of the fuel (kg/s).

This section will only examine data from the Cone Calorimeter experiments performed by Pau [30] since he included the Helium-Neon laser light-extinction measurements and Hill [31] did not.

The yield of soot for the MDF specimen can be seen in Figure 87.

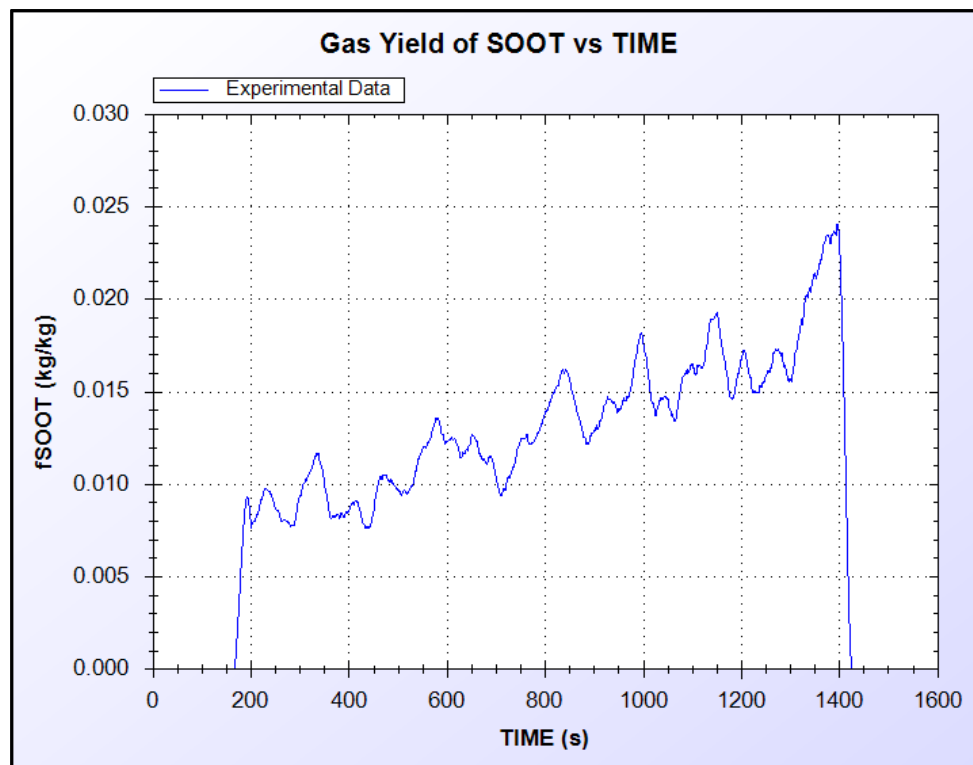




**Figure 87: Soot Yield for MDF**

The peak and average yield of soot for the MDF specimen was calculated to be 0.00893 kg/kg and 0.00540 kg/kg respectively. *The SFPE handbook of Fire Protection Engineering* [37] does not list a value for the yield of soot for MDF.

The yield of soot for PMMA can be seen in Figure 88.



**Figure 88: Soot Yield for PMMA**

The peak and average yield of soot for the PMMA specimen was calculated to be 0.0241 kg/kg and 0.0131 kg/kg respectively. The yield of soot from *The SFPE Handbook of Fire Protection Engineering* [37] for PMMA is 0.022 kg/kg which is within the range of the average and peak yield of soot calculated by UCFIRE.

### 7.3.6 Averages

The average of all, but a few exceptions, time series or other series are calculated with the following algorithm shown in Figure 89.

```
Public Function AVG(ByVal Yvalues As String) As String
' Calculate the average value for a TimeSeries or OtherSeries
starting and ending at a nonzero value.

Dim result As Double = 0
Dim Tempy() As Double = ConvertToDouble(Yvalues)
Dim n As Integer = 0
Dim max As Double = 0
Dim peak As Integer = 0
Dim endpt As Integer = Tempy.Length - 1
Dim startpt As Integer = 0

' Find the peak.
For i As Integer = 0 To Tempy.Length - 1
    If Tempy(i) > max Then
        max = Tempy(i)
        peak = i
    End If
Next

' Work forwards to find the last positive value.
For i As Integer = peak To Tempy.Length - 1
    If Tempy(i) <= 0 Then
        endpt = i-1
        Exit For
    End If
Next

' Work backwards to find the first positive value.
For i As Integer = peak To 0 Step -1
    If Tempy(i) <= 0 Then
        startpt = i+1
        Exit For
    End If
Next

' Calculate the average.
For i As Integer = startpt To endpt
    If Double.IsNaN(Tempy(i)) = False Then
        result = Tempy(i) + result
    End If
Next

result = result / (endpt - startpt)
result = Round(result, sf)

Return CType(result, String)

End Function
```

Figure 89: VB.NET Code to Calculate the Average Value

The Cone Calorimeter Standard (*ASTM E 1354-02*) requires that the average Heat Release Rate values for the first 60, 180, and 300s after ignition or the least negative value of the Heat Release Rate. The Visual Basic.NET code required to calculate the new end point is shown in Figure 90.

```
' Calcualte the end point.  
Dim period As Integer = 60  
endpt = startpt + CType(period / dt, Integer)
```

**Figure 90: Modified End Point**

The Cone Calorimeter standard requires that the trapezium rule be used for the integration so the last section of Figure 89 was modified to perform this calculation as shown in Figure 91.

```
' Calculate the average  
For i As Integer = startpt To endpt  
    temp = CType(Tempy(i), Double) + temp  
Next  
  
' Add half the first and last measurements to the total.  
temp = 0.5 * CType(Tempy(startpt), Double) + temp  
temp = 0.5 * CType(Tempy(endpt), Double) + temp  
temp = (temp * dt) / period  
temp = Round(temp, sf)  
  
Return CType(result, String)
```

**Figure 91: Modified Section Code Showing the Trapezium Rule for Integration**

## 7.4 Ignitability Analysis

### 7.4.1 Procedure for Ignitability Data Reduction

Mikkola and Wichman [39] developed a theory of ignition from first principles by solving the differential form of the heat transfer equation in order to provide a theoretical foundation for the ignition of solid materials.

To deduce from the ignition data whether a material is thermally thin or thick; it is necessary to plot  $t_{ig}^{-1}$  versus  $\dot{q}_e''$  and plot  $t_{ig}^{-0.5}$  versus  $\dot{q}_e''$ . If the  $R^2$  value of the first plot is larger than or equal to the second plot then the solid is thermally-thin, else it is thermally-thick.

The critical flux is simply the negative intercept of the plot over the slope of the plot, Equation 7.17.

$$\dot{q}_{cr}'' = \text{Intercept} / \text{Slope} \quad (7.17)$$

For the thermally thick case the thermal inertia ( $k\rho c$ ) can be calculated with Equation 7.18.

$$k\rho c = \frac{4}{\pi} \left[ \frac{1}{\text{Slope}(T_{ig} - T_{\infty})} \right]^2 \quad (7.18)$$

For the thermally thick case the ignition temperature can be calculated using the procedure developed in Chapter 7.4.2 of this thesis.

### 7.4.2 Minimum Temperature for Ignition

The theory of ignition used assumes that ignition occurs when the surface of the specified material reaches a critical value. This temperature can be found by performing an energy balance on the surface of the material which yields Equation 7.19.

$$\dot{q}_{ig}'' = h_c(T_{ig} - T_\infty) + \sigma(T_{ig}^4 - T_\infty^4) \quad (7.19)$$

Where

- $\dot{q}_{ig}''$  = The flux to cause ignition (kW/m<sup>2</sup>).
- $h_c$  = The convection coefficient (15 W/m<sup>2</sup>) [26].
- $T_{ig}$  = The temperature of the surface of the material at ignition (K).
- $T_\infty$  = The ambient temperature (K).
- $\sigma$  = The Stefan-Boltzman constant ( $\sigma = 5.670 \times 10^{-8} \text{ W / m}^2 \text{ K}^4$ ) [27].

Note that this equation is equivalent to Equation 7.20:

$$F(T_{ig}) = h_c(T_{ig} - T_\infty) + \sigma(T_{ig}^4 - T_\infty^4) - \dot{q}_{ig}'' = 0 \quad (7.20)$$

This method is illustrated in the following section of VB.NET code shown in Figure 92.

```
Function Temperature(ByVal QMIN As Double, ByVal Tamb As Double) As Double

Dim result As Double = 0
Dim sigma As Double = 0.0000000567
Dim hc As Double = 15
Dim Expression1 As Double = 0
Dim Expression2 As Double = 0
QMIN = QMIN * 1000 ' W/m^2

For T As Integer = 100 To 1000 Step 1
    Expression1 = hc * ((T - 1) - Tamb) + sigma *
        ((T - 1) ^ 4 - Tamb ^ 4) - QMIN
    Expression2 = hc * (T - Tamb) + sigma * (T ^ 4 - Tamb ^ 4) - QMIN
    result = T

    If Expression1 < 0 And Expression2 > 0 Then
        Exit For
    End If
Next

Return result

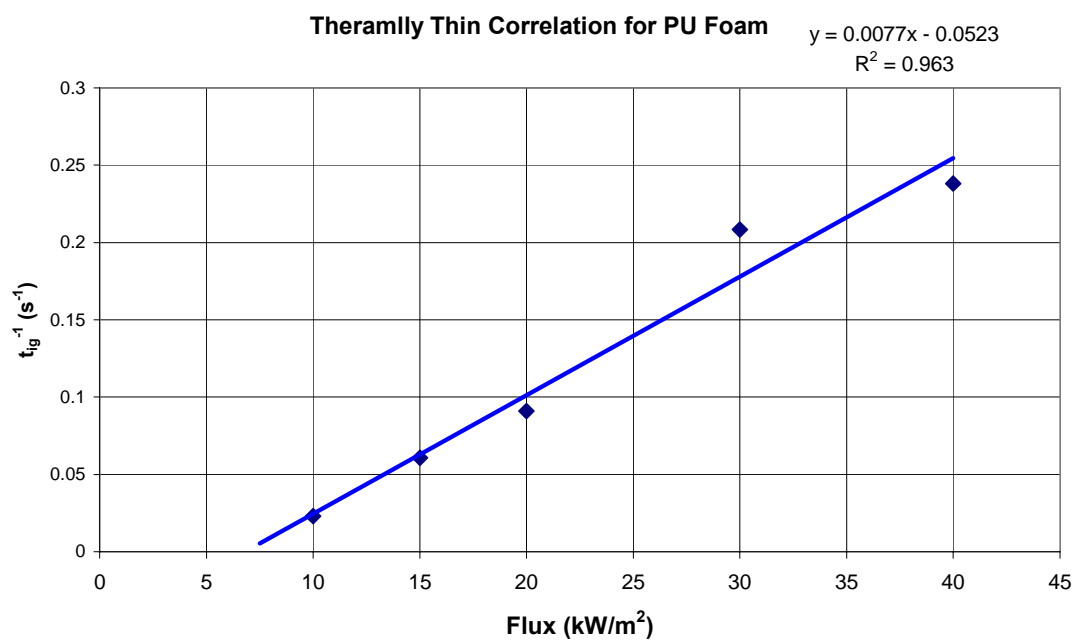
End Function
```

**Figure 92: LIFT Ignition Temperature Code**

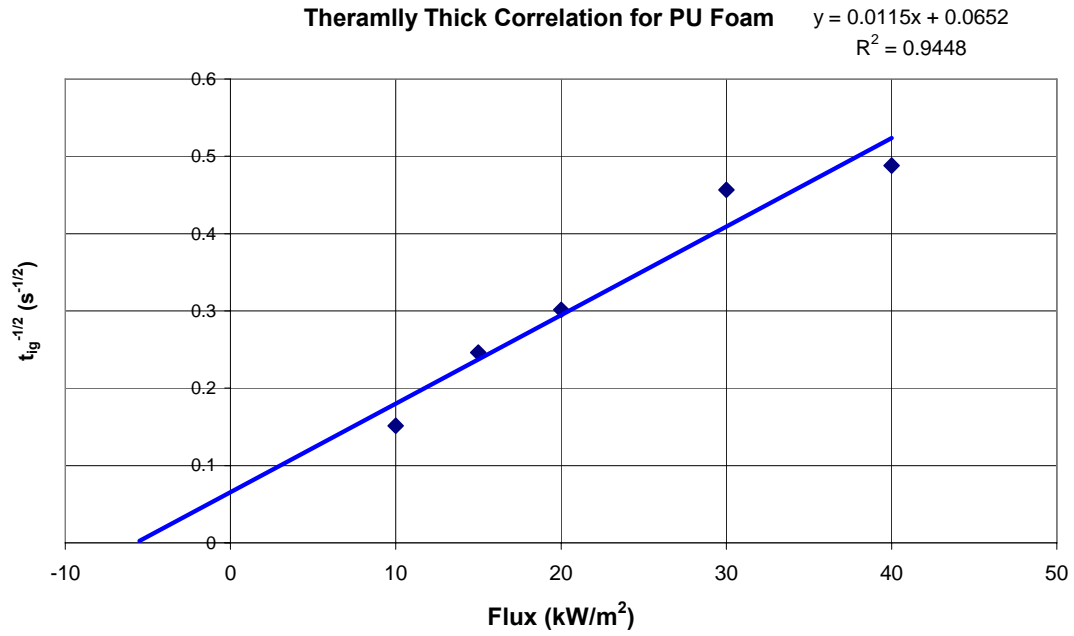
The Visual Basic.NET process starts at 100 K and works its way up to 1000 K in steps of 1 degree Kelvin. The value of  $T_{ig}$  that satisfies this equation occurs when function  $F(T_{ig})$  changes from being a negative number to a positive number.

### 7.4.3 Manual Calculation of Ignitability Parameters

The plot of the thermally thin correlation can be seen in Figure 93, and the plot of the thermally thick correlation can be seen in Figure 94.



**Figure 93: Thermally Thin Correlation for PU Foam**



**Figure 94: Thermally Thick Correlation for Polyurethane Foam**

It can be seen that with a  $R^2$  value of 0.963 the thermally-thin correlation is a better fit to the ignition data for the polyurethane foam specimen than the thermally-thick correlation with an  $R^2$  value of 0.945.

The critical flux is therefore:

$$\dot{q}_{cr}'' = \frac{-0.0523}{0.0077} = 6.79 \text{ kW} / \text{m}^2$$

This value for the critical flux agrees with the value produced by UCFIRE of  $\dot{q}_{cr}'' = 6.81 \text{ kW} / \text{m}^2$ .



## 7.5 LIFT Analysis

The Lateral Ignition and Flame Transport (LIFT) test determines a given material's thermal properties related to piloted ignition of a vertically orientated sample under a constant and uniform heat flux, and to lateral flame spread on a vertical surface due to an externally applied radiant flux [26].

The theory of ignition used by the standard relies on two key assumptions [26]:

- Most common organic solids can be represented as a semi-infinite solid.
- Ignition occurs when the surface of the material reaches a critical temperature  $T_{ig}$ .

The material properties that can be determined are as follows:

- The minimum flux for ignition  $\dot{q}_{ig,min}''$  (kW/m<sup>2</sup>).
- The critical flux for ignition  $\dot{q}_{ig,crit}''$  (kW/m<sup>2</sup>).
- The heat loss coefficient  $h$  (kW/m<sup>2</sup>K).
- The thermal inertia  $k\rho c$  ((kW/m<sup>2</sup>K)<sup>2</sup>s).
- The minimum temperature for ignition  $T_{ig}$  (K).
- The minimum flux for flame spread  $\dot{q}_{s,min}''$  (kW/m<sup>2</sup>).
- The minimum temperature for flame spread  $T_{s,min}$  (K).
- The flame heating parameter  $\Phi$  (kW<sup>2</sup>/m<sup>3</sup>)

### 7.5.1 Procedure for LIFT Ignition Data Reduction

The following steps need to be performed to determine the ignition parameters:

1. Calculate the minimum flux  $\dot{q}_{ig,min}''$  by the 2 kW/m<sup>2</sup> bracketing method.
2. Plot  $\dot{q}_{ig}'' / \dot{q}_e''$  versus  $\sqrt{t}$  and fit a straight line to this dataset to determine  $b$  and  $t^*$ .
3. Determine  $T_{ig}$ .
4. Calculate  $h$ ,  $k\rho c$ .

Where

$$h = \frac{\dot{q}_{ig, \min}''}{T_{ig} - T_{\infty}} \quad (7.21)$$

$$k\rho c = \frac{4}{\pi} \left( \frac{h}{b} \right)^2 \quad (7.22)$$

5. Plot  $\dot{q}_e''$  versus  $1/\sqrt{t}$  and Fit a straight line to this line to determine  $\dot{q}_{ig, crit}''$ .

### 7.5.2 Manual Calculation of LIFT Ignition Parameters

The principles of manual LIFT ignition data reduction shall be reviewed with the 18 mm MDF specimen used by Merryweather [25]. The ignition data can be seen in Table 17.

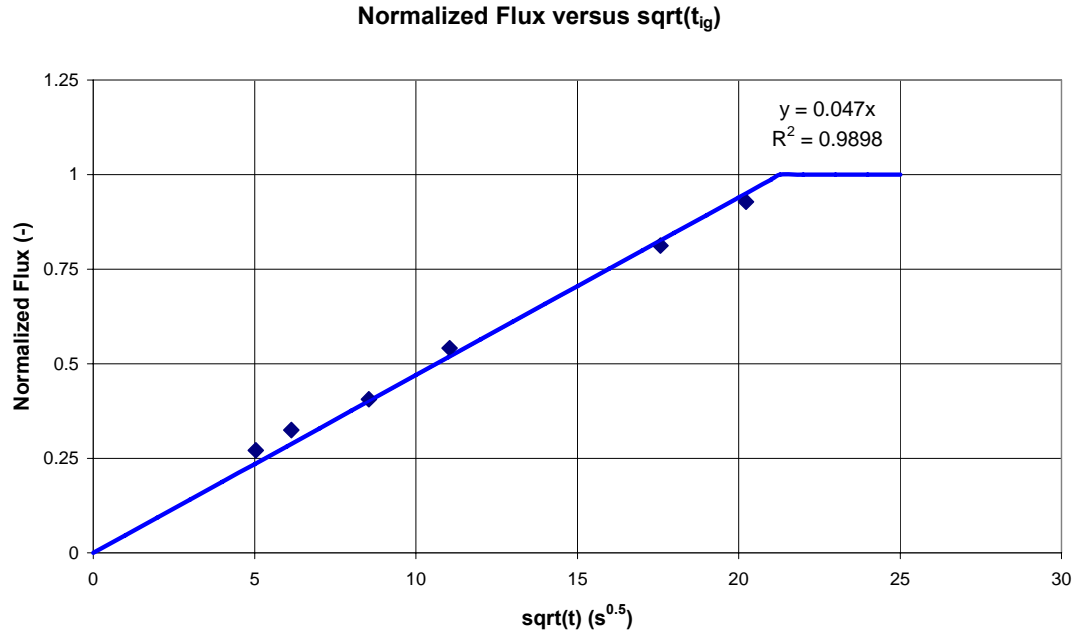
Heat flux (kW/m <sup>2</sup> )	Time to ignition (s)
12.5	No ign.
15	No ign.
17.5	409
20	309
30	122
40	73
50	37.7
60	25.4

**Table 17: MDF Ignition Data**

1. Firstly the minimum flux is:

$$\dot{q}_{ig, \min}'' = \frac{(15 + 17.5)}{2} = 16.25 \text{ kW} / \text{m}^2$$

2. The plot of  $\dot{q}_{ig}'' / \dot{q}_e''$  versus  $\sqrt{t}$  can be seen in Figure 95.



**Figure 95:  $\dot{q}_{ig}'' / \dot{q}_e''$  versus  $\sqrt{t}$**

From Figure 95 it can be found that  $b = 0.047s^{0.5}$  and

$$t^* = \left( \frac{1}{b^2} \right) = \left( \frac{1}{0.047^2} \right) = 453s$$

3. The iterative method discussed in Chapter 7.4.2 can be used to determine the minimum ignition temperature for the MDF specimen. The parameters required for the calculation can be seen in Table 18, and the results of the calculation can be seen in Table 19.

<b>sigma</b>	5.67E-08	W/m <sup>2</sup> K <sup>4</sup>
<b>hc</b>	15	kW/m <sup>2</sup>
<b>Tamb</b>	291	K
<b>qmin</b>	16250	W/m <sup>2</sup>

**Table 18:  $F(t_{ig})$  Set up Parameters**

<b>T</b>	<b>F(t<sub>ig</sub>)</b>
656	-681
657	-602
658	-523
659	-443
660	-363
661	-283
662	-202
663	-121
<b>664</b>	<b>-40</b>
<b>665</b>	<b>42</b>
666	124
667	206
668	288
669	371

**Table 19: Iterative Approach to Determine  $T_{ig}$**

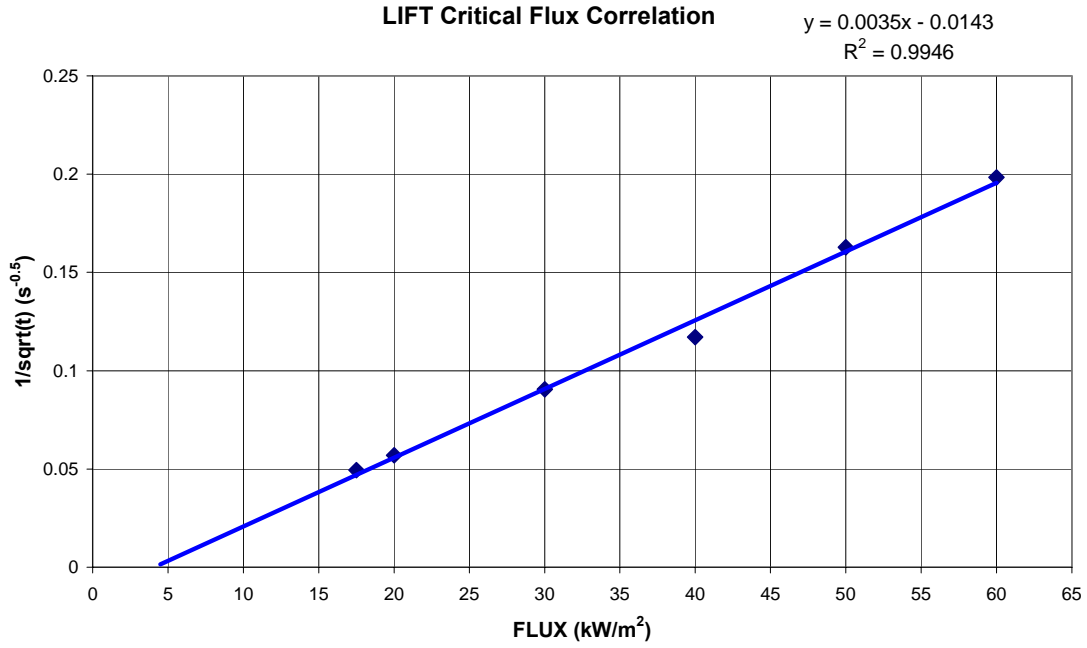
Note that the last temperature to cause the function  $F(t_{ig})$  to be less than zero is 664 K and the first temperature to cause the function  $F(t_{ig})$  to be greater than zero is 665 K. Taking the average of these two values and rounding up yields an ignition temperature of 665 K.

4. Calculating  $h$  and  $k\rho c$  :

$$h = \frac{\dot{q}_{ig,min}''}{T_{ig} - T_{\infty}} = \frac{16.25kW / m^2}{665K - 291K} = 0.434kW / m^2 K$$

$$k\rho c = \frac{4}{\pi} \left( \frac{h}{b} \right)^2 = \frac{4}{\pi} \left( \frac{0.434}{0.047} \right)^2 = 1.09$$

5. The plot  $\dot{q}_e''$  versus  $1/\sqrt{t}$  can be seen in Figure 96.



**Figure 96: LIFT Critical Flux Correlation**

From Figure 96 it can be found that the x-intercept is:

$$\dot{q}_{ig,crit}'' = \frac{-(-0.0143)}{0.0035} = 4.09 \text{ kW} / \text{m}^2$$

### 7.5.3 Procedure for LIFT Flame Spread Data Reduction

The following steps need to be performed to determine the LIFT flame spread parameters:

1. Construct the shape function  $F(x)$  and find  $\dot{q}_e''(x)$ .
2. Compute the flame front velocity  $V$  with Equation 7.23.

$$3. \quad V = \frac{\sum tx - \frac{\sum t \sum x}{3}}{\sum t^2 - \frac{(\sum t)^2}{3}} \quad (7.23)$$

4. Plot the linear section of  $V^{-0.5}$  versus  $\dot{q}_e''(x)F(t)$  and determine  $\Phi$ ,  $\dot{q}_{s,\min}''$ , and  $\dot{q}_{ig,\min}'' \cdot \dot{q}_{s,\min}''$  is the value of  $\dot{q}_e''(x)F(t)$  that occurs at the last position  $x$  that a flame is still present.

5. Where

$$6. \quad \Phi = \frac{4/\pi}{(Cb)^2} \quad (7.24)$$

$$7. \quad F(t) = \begin{cases} b\sqrt{t}, & t \leq t^* \\ 1, & t \geq t^* \end{cases} \quad (7.25)$$

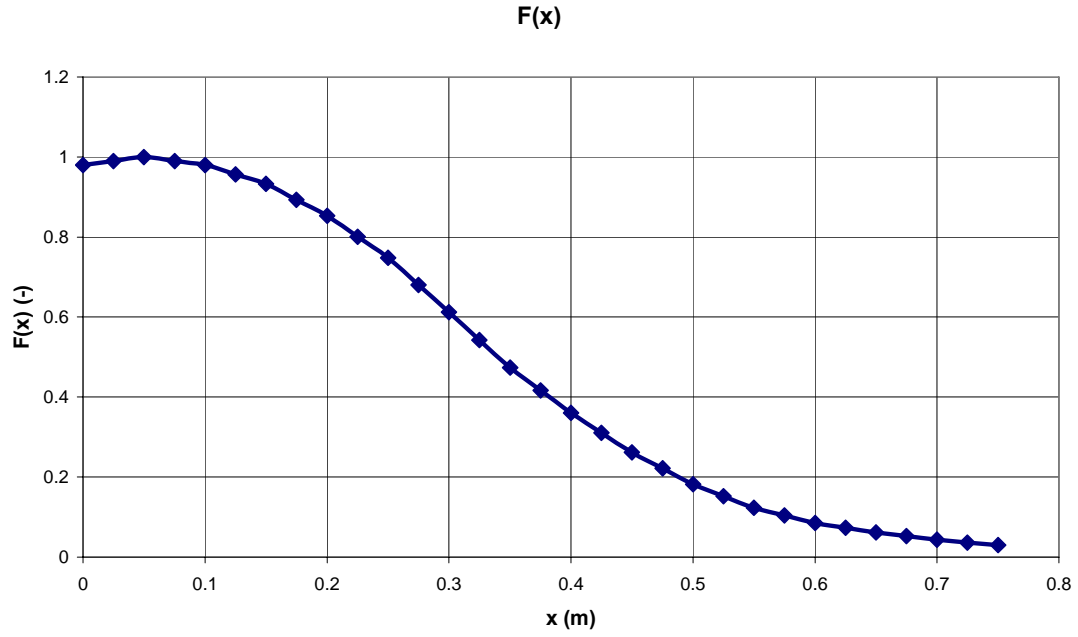
8. Determine  $T_{ig}$ .

These steps will be explained in the next section but steps 2, 5 and 8 deserve their own chapters; Chapters 8 - 10 of this thesis.

#### 7.5.4 Manual Calculation of LIFT Flame Spread Parameters

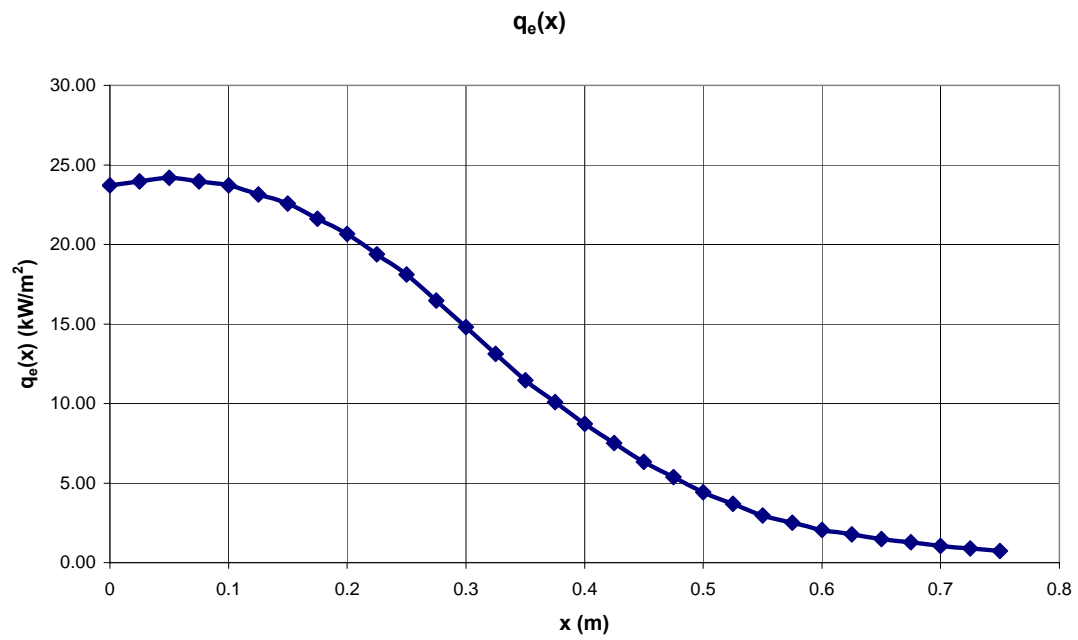
The principles of manual LIFT flame spread data reduction shall be reviewed with the 18 mm MDF specimen used by Merryweather [25].

1. The shape function  $F(x)$  can be seen in Figure 97.



**Figure 97: Shape Function  $F(x)$**

With  $\dot{q}_e''(50mm) = 24.2kW / m^2$ ,  $\dot{q}_e''(x)$  can be seen in Figure 98.



**Figure 98:  $\dot{q}_e''(x)$**

- Three flame spread tests were performed and the resulting values of  $\dot{q}_e''(x)F(t)$  and  $V^{-0.5}$  can be seen in Tables 20-22.

Flame Front Position x (m)	Time to position t (s)	Time from ignition (s)	V (m/s)	F(t)	Q	Q*F(t)	1/√V
0.05	479	0					
0.075	479	0					
0.1	479	0					
0.125	479	0					
0.15	479	0					
0.175	479	0					
0.2	479	0					
0.225	482	3					
0.25	488	9	0.0049	1	18.11	18.11	14.24
0.275	492	13	0.00098	1	16.46	16.46	31.99
0.3	530	51	0.00059	1	14.81	14.81	41.05
0.325	576	97	0.00045	1	13.13	13.13	47.11
0.35	640	161	0.00038	1	11.45	11.45	51.39
0.375	708	229	0.00029	1	10.09	10.09	58.89
0.4	811	332	0.00021	1	8.72	8.72	68.57
0.425	942	463	0.00015	1	7.52	7.52	80.85
0.45	1134	655	0.00012	1	6.33	6.33	90.53
0.46	1232	753				5.85	

Table 20: Flame Spread Test 1 (Ignition Time 479 s)

Flame Front Position x (m)	Time to position t (s)	Time from ignition (s)	V (m/s)	F(t)	Q	Q*F(t)	1/√V
0.05	478	0					
0.075	478	0					
0.1	478	0					
0.125	478	0					
0.15	478	0					
0.175	478	0					
0.2	478	0					
0.225	478	0					
0.25	478	0					
0.275	487	9					
0.3	515	37	0.00072	1	14.81	14.81	37.37
0.325	556	78	0.00054	1	13.13	13.13	42.98
0.35	607	129	0.00038	1	11.45	11.45	51.60
0.375	687	209	0.00025	1	10.09	10.09	63.14
0.4	804	326	0.00021	1	8.72	8.72	69.29
0.425	927	449	0.00014	1	7.52	7.52	84.06
0.441	1089	611				6.76	

Table 21: Flame Spread Test 2 (Ignition Time 478 s)



Flame Front Position x (m)	Time to position t (s)	Time from ignition (s)	V (m/s)	F(t)	Q (kW/m <sup>2</sup> )	Q*F(t)	1/√V
0.05	455	0					
0.075	455	0					
0.1	455	0					
0.125	455	0					
0.15	455	0					
0.175	455	0					
0.2	455	0					
0.225	455	0					
0.25	455	0					
0.275	466	11					
0.3	487	32	0.00082	1	14.81	14.81	34.82
0.325	525	70	0.00055	1	13.13	13.13	42.60
0.35	577	122	0.00044	1	11.45	11.45	47.59
0.375	638	183	0.00031	1	10.09	10.09	56.70
0.4	735	280	0.00023	1	8.72	8.72	66.65
0.425	859	404	0.00017	1	7.52	7.52	76.28
0.45	1024	569	0.00013	1	6.33	6.33	87.30
0.457	1109	654				5.99	

Table 22: Flame Spread Test 3 (Ignition Time 455 s)

3. The plot of  $V^{-0.5}$  versus  $\dot{q}_e''(x)F(t)$  can be seen in Figure 99.

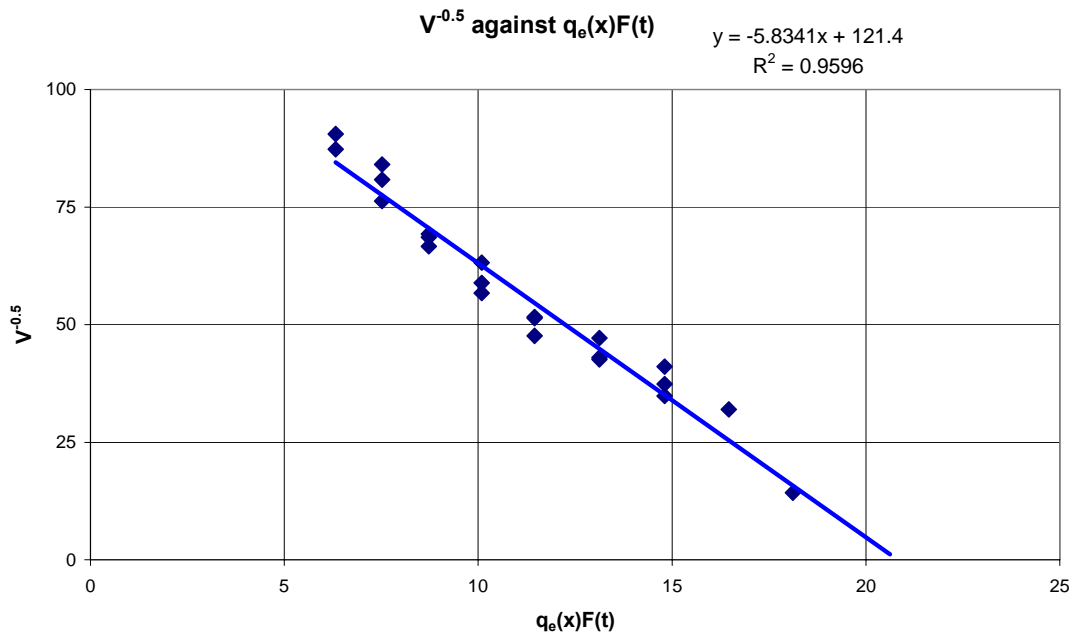


Figure 99:  $V^{-0.5}$  against  $q_e(x)F(t)$

4. From Figure 99 it does not appear necessary to need to remove data points from this curve. From Figure 99 it can be found that the x-intercept is:

$$\dot{q}_{ig,min}'' = \frac{-(121.4)}{-5.83} = 20.8 \text{ kW/m}^2$$

The slope of this graph is  $C = -5.83s^{1/2}m^{3/2}kW^{-1}$  so:

$$\Phi = \frac{4/\pi}{(Cb)^2} = \frac{4/\pi}{(-5.83 \times 0.047)^2} = 16.96kW^2m^{-3}$$

$\dot{q}_{s,min}''$  is the average of the last value of  $\dot{q}_e''(x)F(t)$  for each table (Tables 20-22):

$$\dot{q}_{s,min}'' = \frac{5.85 + 6.76 + 5.99}{3} = 6.2kW/m^2$$

5. The iterative method discussed in Chapter 7.4.2 can be used to determine the minimum temperature for flame spread for the MDF specimen. The parameters required for the calculation can be seen in Table 23, and the results of the calculation can be seen in Table 24.

<b>sigma</b>	5.67E-08	
<b>hc</b>	15	kW/m <sup>2</sup>
<b>Tamb</b>	291	K
<b>qmin</b>	6200	W/m <sup>2</sup>

**Table 23:  $F(t_{ig})$  Setup Parameters**

<b>T</b>	<b>F(t<sub>ig</sub>)</b>
491	-311
492	-269
493	-227
494	-185
495	-142
496	-99.9
497	-57.1
498	-14.2
499	28.9
500	72.2
501	116

**Table 24: Iterative Approach to Determine  $T_{ig}$**

Note that the last temperature to cause the function  $F(t_{ig})$  to be less than zero is 498 K and the first temperature to cause the function  $F(t_{ig})$  to be greater than zero is 499 K. Taking the average of these two values and rounding up yields a minimum temperature for flame spread of 499 K.

### 7.5.5 Summary of LIFT Ignition and Flame Spread Parameters

These values compared with those produced by UCFIRE shown in Table 25.

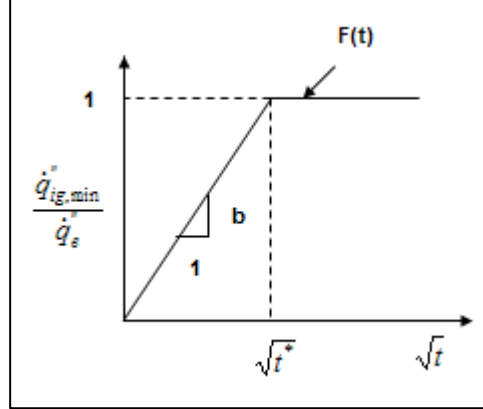
Parameter	Manual Calculation	FIREBASE
$b \text{ (s}^{0.5}\text{)}$	0.047	0.048
$t^* \text{ (s)}$	453	434
$k\rho c \text{ (kJ}^2\text{m}^{-4}\text{K}^{-2}\text{s}^{-1}\text{)}$	1.09	1.09
$\dot{q}_{ig,min}'' \text{ (kW/m}^2\text{)}$	16.3	16.3
$\dot{q}_{ig,crit}'' \text{ (kW/m}^2\text{)}$	4.09	4.08
$h \text{ (kWm}^{-2}\text{K)}$	0.043	0.044
$T_{ig} \text{ (K)}$	665	666
$C \text{ (s}^{1/2}\text{m}^{3/2}\text{kW}^{-1}\text{)}$	-5.83	5.84
$\dot{q}_{s,min}'' \text{ (kW/m}^2\text{)}$	6.2	6.2
$\Phi \text{ (kW}^2\text{m}^{-3}\text{)}$	17.0	16.9
$T_{s,min} \text{ (K)}$	499	499

**Table 25: Comparison of MDF (18mm) LIFT Ignition Parameters**

In this section the ignition and flame spread correlation data points seemed to following the fitted straight line so that by eye it did not seem necessary to remove any data points; however this will not always be the case. Chapter 8, 9 and 10 of this thesis will develop and validate a method of automatically scrutinizing these three LIFT correlations.

## 8 Scrutinizing the Thermal Response Correlation

The ASTM standard for the LIFT data reduction (*ASTM E 1321-97a*) requires that a straight line should be fitted to the Thermal Response Correlation, so that the plot resembles Figure 100.



**Figure 100: Thermal Response Correlation**

Where

$$\frac{\dot{q}_{ig,min}''}{\dot{q}_e''} = F(t) = \begin{cases} b\sqrt{t}, & t \leq t^* \\ 1, & t > t^* \end{cases} \quad (10.1)$$

Babrauskas and Wetterlund [34] investigated this correlation and noted: “*it is clear that the sloping-line segment should follow only the initial set of data points. Data points for large values of  $\sqrt{t}$  are not to follow the sloping line segment but rather should end up fitting to the subsequent horizontal line segment. Unfortunately the standard gives no guidance on how this data fitting should be done.*”

The following section of this thesis solves this problem by developing an unbiased and mechanistic method of scrutinizing LIFT ignition data without human intervention.

## 8.1 Linear Regression

It may be possible to apply a linear first order model [40], to the dataset produced by plotting  $\frac{\dot{q}_{ig,min}''}{\dot{q}_e''}$  against  $\sqrt{t}$ , as shown in Equation 8.1.

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (8.1)$$

Where  $\beta_0$  and  $\beta_1$  are both constants and  $\varepsilon$  is the random error term i.e. how the model deviates from the real data points. These terms are all unknown and can only be estimated from the experimental observations. Thus Equation 8.1 can be estimated with Equation 8.2

$$\hat{Y} = b_0 + b_1 X \quad (8.2)$$

Where  $\hat{Y}$  is the predicted value of  $Y$  for constants  $b_0$  and  $b_1$ , and the given vector  $X$ . Note that  $b_0$  and  $b_1$  are estimates of  $\beta_0$  and  $\beta_1$ , and contain some residual error  $\hat{\varepsilon}$ .

The sum of the squared random error term is given by the subtracting the predicted values ( $\hat{Y}$ ) from the real values ( $Y$ ), squaring each value and then summing all the values to yield Equation 8.3.

$$S = \sum_{i=1}^n \varepsilon_i^2 = \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i)^2 \quad (8.3)$$

To obtain values of estimates  $b_0$  and  $b_1$  that minimize this function  $S$ , Equation 8.3 can be differentiated with respect to  $\beta_0$  and then with respect to  $\beta_1$  and these equations can be set to zero to obtain Equations 8.4 and 8.5.

$$\frac{\partial S}{\partial \beta_0} = -2 \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i) = 0 \quad (8.4)$$

$$\frac{\partial S}{\partial \beta_1} = -2 \sum_{i=1}^n X_i (Y_i - \beta_0 - \beta_1 X_i) = 0 \quad (8.5)$$

The LIFT Thermal Response correlation requires that the fitted straight line goes through the origin of the graph. This can be done by substituting  $b_0 = \beta_0 = 0$ ,  $b_1 = \beta_1$  into Equations 8.4 and 8.5, recognising that this system of equations is now over

determined i.e. one unknown in two equations, and solving Equation 11 to yield Equations 8.6

$$b_1 = \frac{\sum_{i=1}^n (X_i Y_i)}{\sum_{i=1}^n (X_i X_i)} \quad (8.6)$$

## 8.2 Zero Mean (ZM) Method

The problem of scrutinising the Thermal Response correlation and determining which points belong on the sloping line can be solved by reviewing the principles of linear regression which relies on a number of assumptions being satisfied so that there is a reasonable approximation to a straight line relationship between two variables [42].

These assumptions are based on the distribution of random errors in the model (Equation 8.7) which can be estimated from the residual error term (Equation 8.8).

$$\varepsilon = Y - E(Y) \quad (8.7)$$

$$\hat{\varepsilon} = Y - \hat{Y} \quad (8.8)$$

These four assumptions are:

- The probability distribution of  $\hat{\varepsilon}$  has zero mean.
- The probability distribution of  $\hat{\varepsilon}$  has constant variance.
- The probability distribution of  $\hat{\varepsilon}$  is normal.
- The value of  $\hat{\varepsilon}$  for one observation is independent of another observation.

Of all of these criteria the first is the easiest to test since LIFT ignition tests often involve small datasets. Thus the linear regression model provides a reasonable approximation to the straight line relationship between two variables, and conversely two variables can reasonably fitted by a straight line, when Equation 8.8 is equal to zero.

The Zero Mean (ZM) algorithm involves:

1. *Using the principles of linear regression; fit a straight line to all the data points in the Thermal Response correlation.*
2. *Calculate the Mean Residual Error (MRE).*
3. *If the Mean Residual Error (MRE) is significantly greater than zero (i.e. the tolerance level) then either remove the right-most data point for averaged ignition data or an entire cluster of values at a single  $\dot{q}_{ig}'' / \dot{q}_e''$  from the right of the plot for clustered datasets.*
4. *Repeat steps 1 - 3 until the MRE is less than or equal to the tolerance level.*
5. *Calculate  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$ .*

Since the linear regression line must go through the origin of the graph, the ZM algorithm should converge to a single solution. Any data points which do not follow the trend of the initial set of data points with a confidence interval of 5 % will be removed by this algorithm. Some important points to note:

- Since rounding error present in all computer calculations it is unreasonable to expect the Mean Residual Error of the correlation to be exactly zero for a linear set for data so a value of 5 % of the maximum value of  $\dot{q}_{ig}'' / \dot{q}_e'' = 1$  was chosen as the stopping point. The significance of this value is that 5 % is considered to be a reasonable amount of error as it is analogous to two standard deviations away from the mean of a normal distribution i.e. the 95 percentile.
- This algorithm was first prototyped using MATLAB and then implemented within UCFIRE.
- For the LIFT Thermal Response correlation we know that the linear regression line must go through the origin. Thus the series of data points should converge to a single solution: a straight line through the origin.

The full code in VB.NET to scrutinise the Thermal Response Correlation can be seen in *Appendix D: ZM Method for the TR Correlation* of this thesis.

### ***8.3 ZM Method Applied to Merryweather's LIFT Data***

This algorithm was firstly evaluated with exemplar LIFT ignition test data from Merryweather's [25] experiments. These experiments included:

- MDF (18 mm).
- Plywood (17 mm).
- Macrocarpa (20 mm).
- Particle Board (20 mm).
- Rimu (20 mm).
- Hardboard (5 mm).



### 8.3.1 MDF (18 mm)

The plot of unscrutinised values of the Thermal Response Correlation for Merryweather's MDF specimen can be seen in Figure 101, and the plot of scrutinised values can be seen in Figure 102.

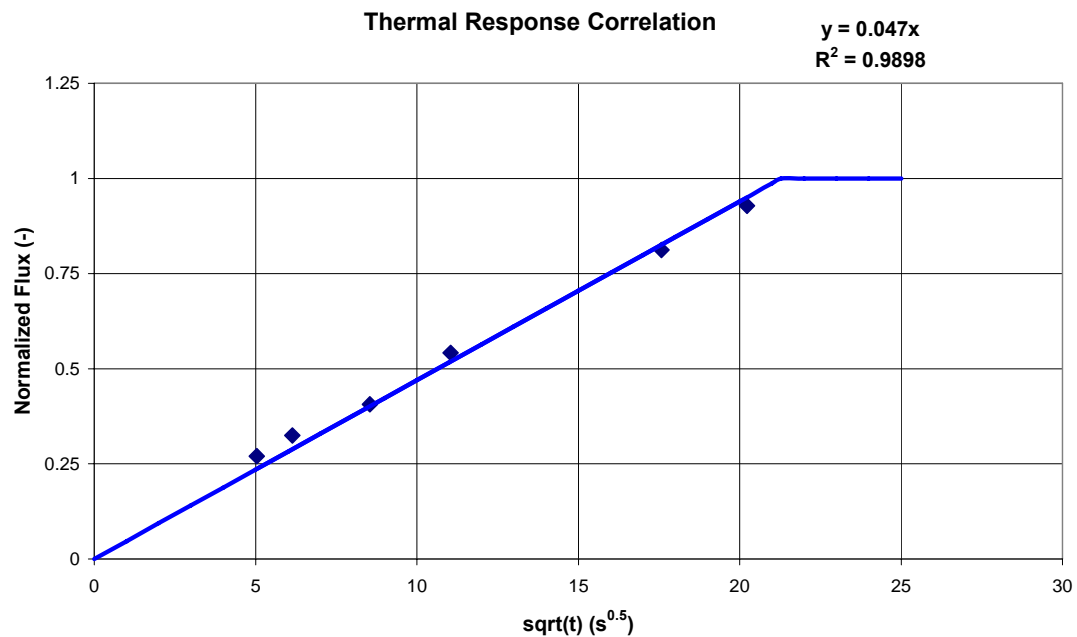


Figure 101: Unscrutinised TR Correlation for MDF

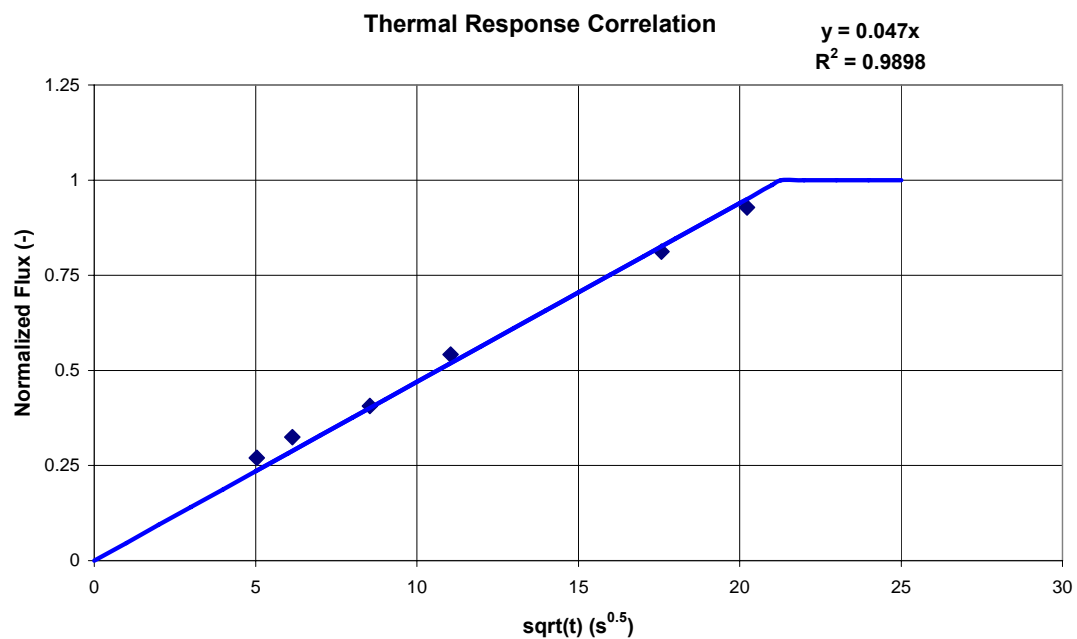


Figure 102: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 26.

Iteration	Mean Residual Error (%)
0*	1.222

**Table 26: MDF (18 mm) Zero-Mean Method Output**

Please note that the asterisk means that the ZM algorithm decided that the current iteration yielded the best results for the given data set.

As Table 26 shows the Mean Residual Error of the Thermal Response correlation was below the threshold value of 5 %; thus there was no need to remove data points from the original TR Correlation plot. When LIFT analysis was performed manually for the MDF specimen in Chapter 7.5 of this thesis it also noted that it was not necessary to remove data points from this correlation.

A comparison of the LIFT ignition parameters found by Merryweather and UCFIRE can be seen in Table 27.

Parameter	Merryweather [43]	UCFIRE
$b \text{ (s}^{0.5}\text{)}$	0.047	0.048
$t^* \text{ (s)}$	456	434
$k\rho c \text{ (kJ}^2\text{m}^{-4}\text{K}^{-2}\text{s}^{-1}\text{)}$	1.10	1.09
$\dot{q}_{ig,min}'' \text{ (kW/m}^2\text{)}$	16.25	16.3
$h \text{ (kWm}^{-2}\text{K)}$	0.044	0.044
$T_{ig} \text{ (K)}$	664	666

**Table 27: Comparison of MDF (18 mm) LIFT Ignition Parameters**

Table 27 makes an interesting point even a slight difference in rounding can have a significant effect on the dependent parameters. For instance a 0.001 difference in the LIFT Ignition parameter  $b$  leads to a 5% difference in the value of the characteristic equilibrium time  $t^*$ . This is why is important to scrutinise the ignition data for data points that violate the zero heat loss requirement of the semi-infinite solid; as even one unsuitable data point may having a significant influence on the trend of the Thermal Response correlation.

### 8.3.2 Plywood (17 mm)

The plot of unscrutinised values of the Thermal Response correlation for Merryweather's Plywood specimen can be seen in Figure 103, and the plot of scrutinised values can be seen in Figure 104.

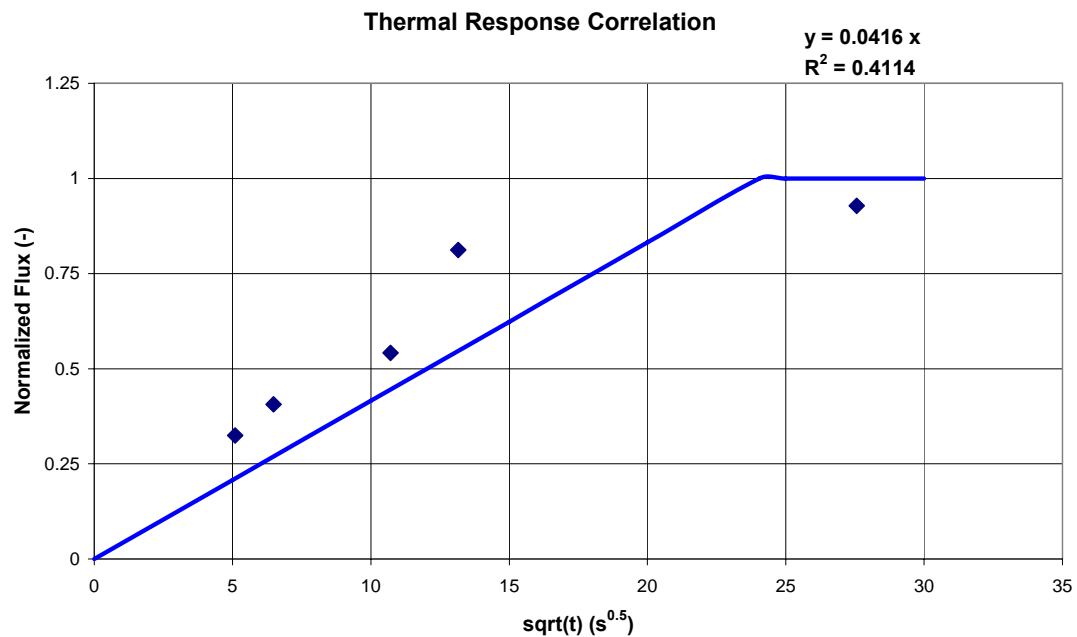


Figure 103: Unscrutinised TR Correlation for Plywood

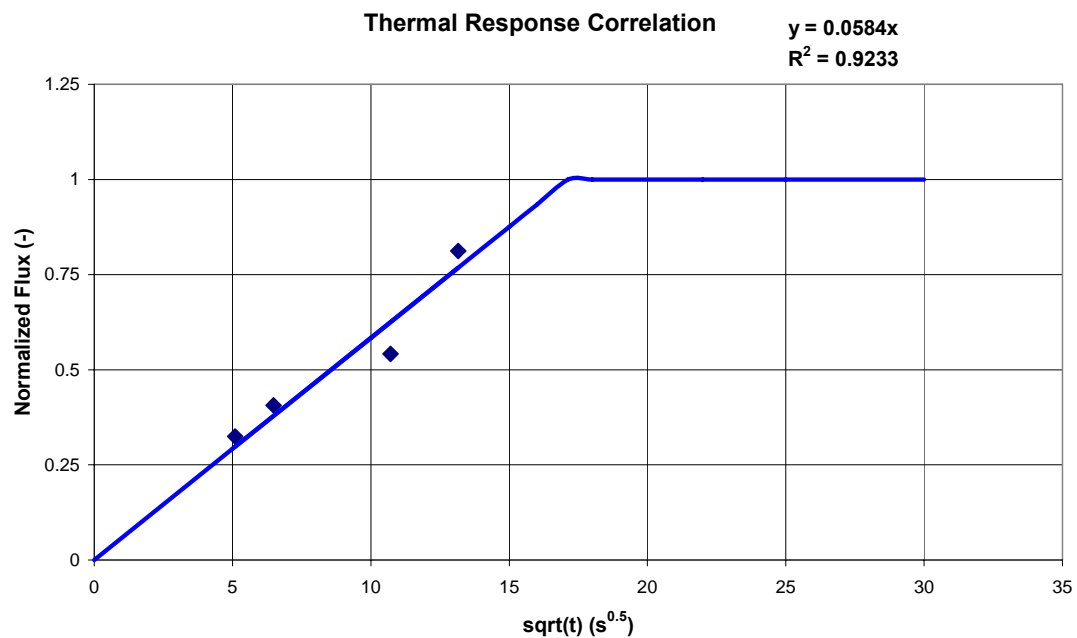


Figure 104: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 28.

Iteration	Mean Residual Error (%)
0	21.7
1 *	4.42

**Table 28: Plywood (17mm) Zero-Mean Method Output**

The Plywood specimen's Mean Residual Error starts at 21.7 % and with the removal of one data point the Mean Residual Error has dropped to 4.42 %, below the tolerance level. After which the  $b$ ,  $t^*$ ,  $k\rho c$ ,  $h$  and  $T_{ig}$  values agree with Merryweather's results as shown in Table 29.

Parameter	Merryweather [43]	UCFIRE
$b$ ( $s^{0.5}$ )	0.058	0.058
$t^*$ (s)	293	291
$k\rho c$ ( $\text{kJ}^2\text{m}^{-4}\text{K}^{-2}\text{s}^{-1}$ )	0.71	0.70
$\dot{q}_{ig,min}''$ ( $\text{kW}/\text{m}^2$ )	16.3	16.3
$h$ ( $\text{kWm}^{-2}\text{K}$ )	0.044	0.044
$T_{ig}$ (K)	664	665

**Table 29: Comparison of Plywood (17 mm) LIFT Ignition Parameters**

### 8.3.3 Macrocarpa (20 mm)

The plot of unscrutinised values of the Thermal Response correlation for Merryweather's Macrocarpa specimen can be seen in Figure 105, and the plot of scrutinised values can be seen in Figure 106.

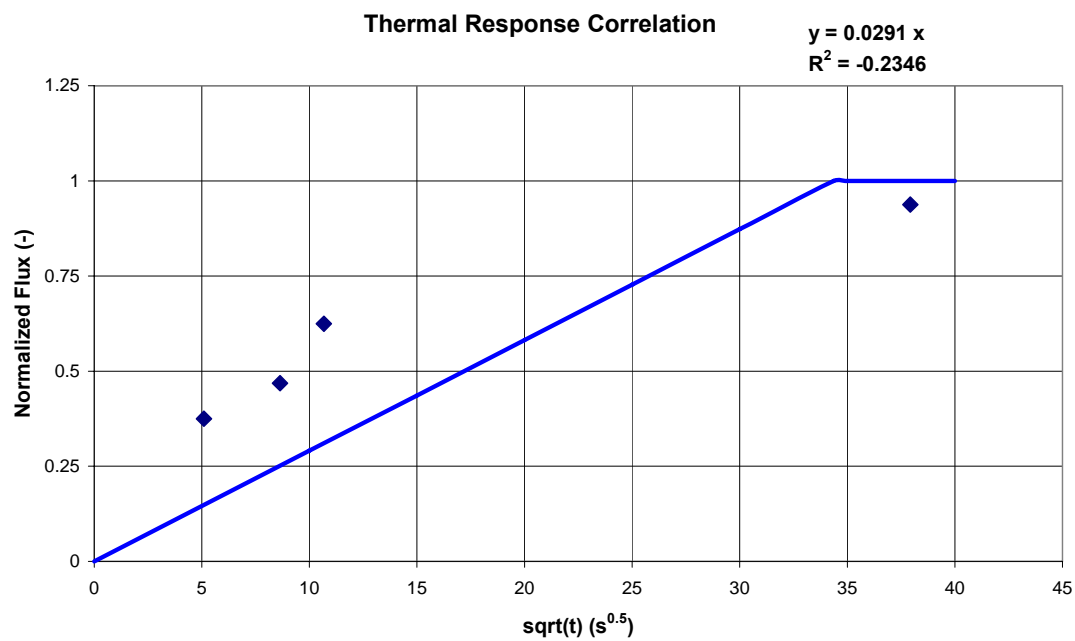


Figure 105: Unscrutinised TR Correlation for Macrocarpa

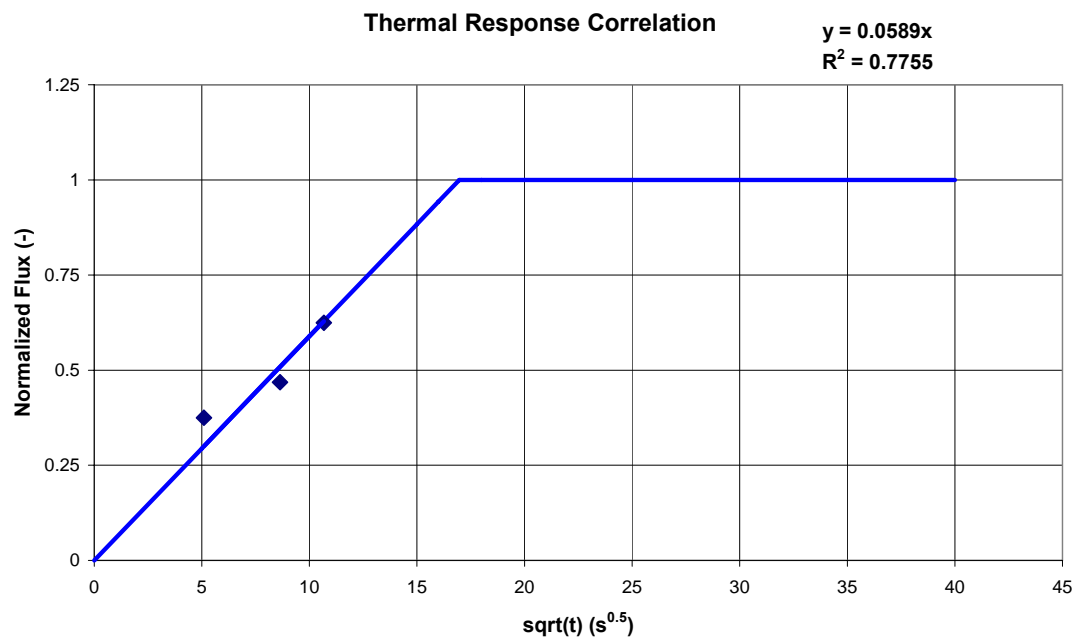


Figure 106: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 30.

Iteration	Mean Residual Error (%)
0	16.8
1*	0.374

**Table 30: Macrocarpa (20 mm) ZM Method Output**

The Macrocarpa specimen's Mean Residual Error started off at 16.8% and with the removal of one data point the Mean Residual Error drops down to 0.374%. After which the  $b$ ,  $t^*$ ,  $k\rho c$ ,  $h$  and  $T_{ig}$  values agree with Merryweather's results as shown in Table 31.

Parameter	Merryweather [43]	UCFIRE
$b$ ( $s^{0.5}$ )	0.059	0.0591
$t^*$ (s)	288	287
$k\rho c$ ( $\text{kJ}^2\text{m}^{-4}\text{K}^{-2}\text{s}^{-1}$ )	0.78	0.8
$\dot{q}_{ig,min}''$ ( $\text{kW}/\text{m}^2$ )	18.75	18.8
$h$ ( $\text{kWm}^{-2}\text{K}$ )	0.046	0.0467
$T_{ig}$ (K)	698	695

**Table 31: Comparison of Macrocarpa (20 mm) LIFT Ignition Parameters**

### 8.3.4 Particle Board (20 mm)

The plot of unscrutinised values of the Thermal Response correlation for Merryweather's Particle Board specimen can be seen in Figure 107, and the plot of scrutinised values can be seen in Figure 108.

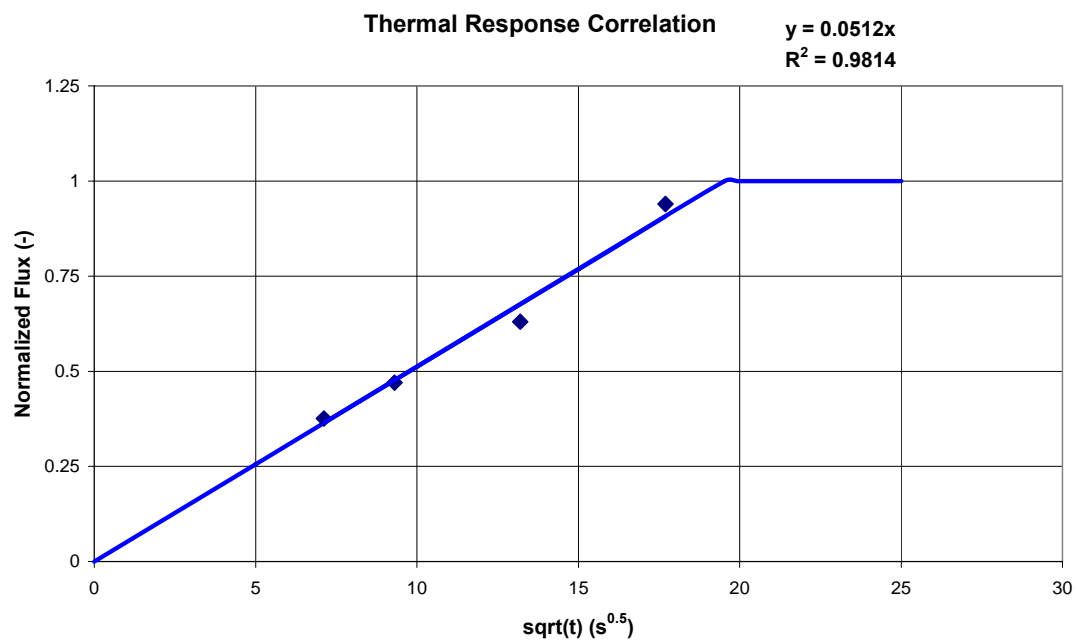


Figure 107: Unscrutinised TR Correlation for Particle Board

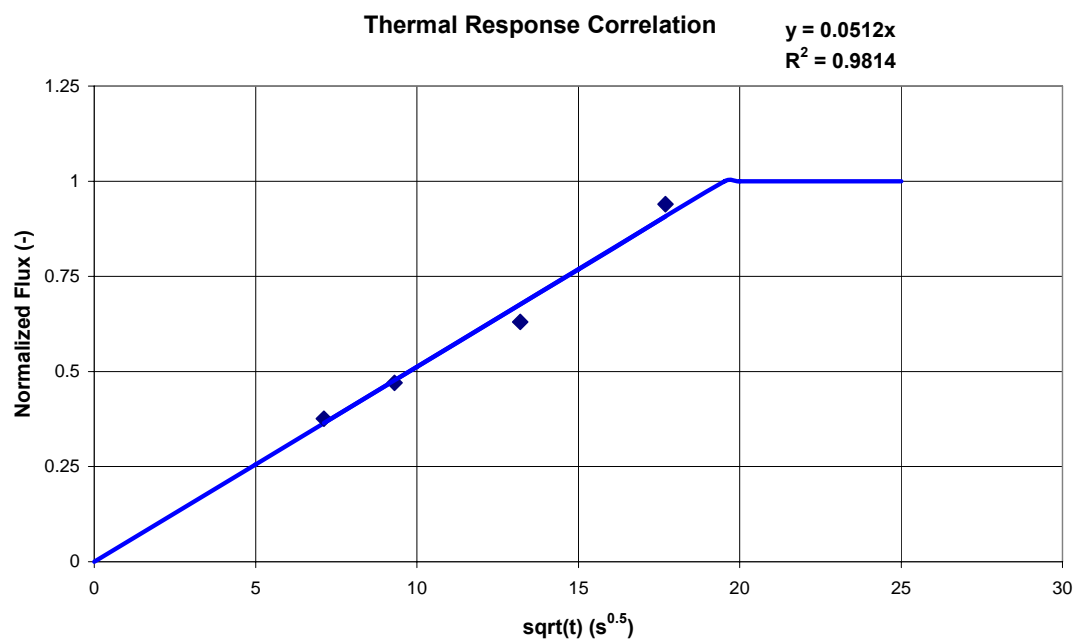


Figure 108: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 32.

Iteration	Mean Residual Error (%)
0*	3.32

**Table 32: Particle Board (20 mm) ZM Method Output**

Particle Board's Mean Residual Error started off at 3.32 % so no points were needed to be removed. After which the  $b$ ,  $t^*$ ,  $k\rho c$ ,  $h$  and  $T_{ig}$  values agree with Merryweather's results as shown in Table 33.

Parameter	Merryweather [43]	UCFIRE
$b$ ( $s^{0.5}$ )	0.051	0.0511
$t^*$ (s)	386	383
$k\rho c$ ( $\text{kJ}^2\text{m}^{-4}\text{K}^{-2}\text{s}^{-1}$ )	0.96	1.05
$\dot{q}_{ig,\min}''$ ( $\text{kW}/\text{m}^2$ )	18.75	18.8
$h$ ( $\text{kWm}^{-2}\text{K}$ )	0.044	0.0465
$T_{ig}$ (K)	698	695

**Table 33: Comparison of Particle Board (20 mm) LIFT Ignition Parameters**



### 8.3.5 Rimu (20 mm)

The plot of unscrutinised values of the Thermal Response correlation for Merryweather's Rimu specimen can be seen in Figure 109, and the plot of scrutinised values can be seen in Figure 110.

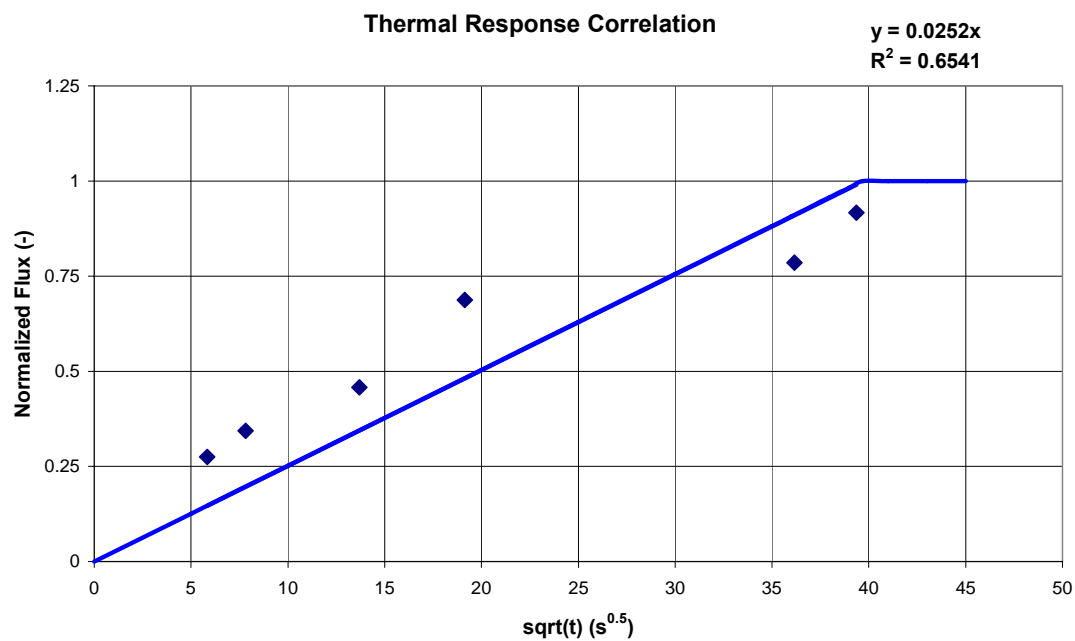


Figure 109: Unscrutinised TR Correlation for Rimu

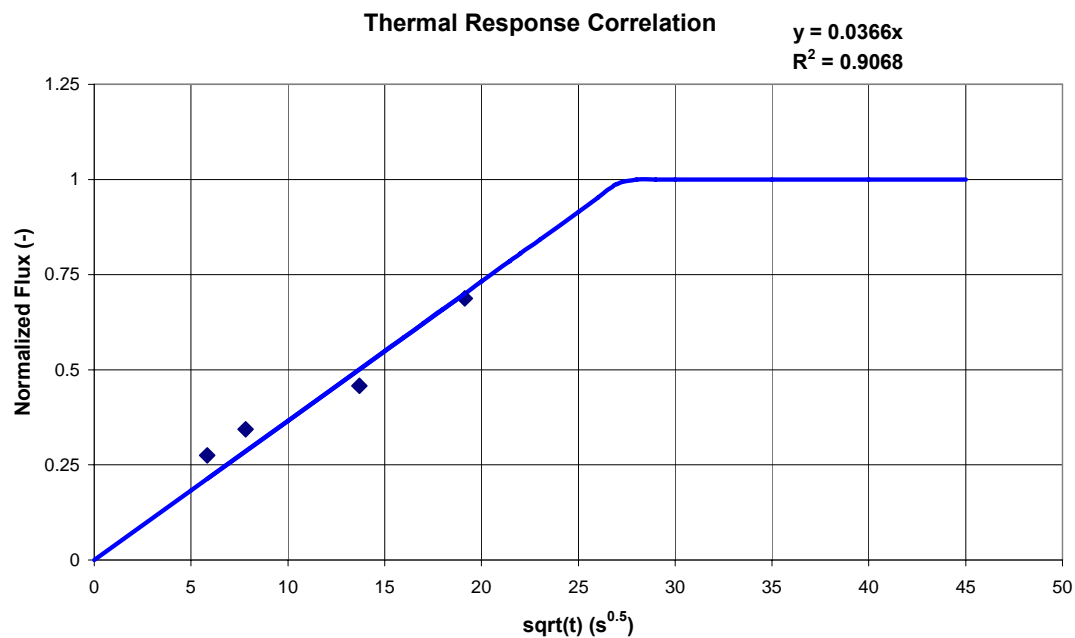


Figure 110: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 34.

Iteration	Mean Residual Error (%)
0	7.37
1	17.8
2*	1.22

**Table 34: Rimu (20mm) Zero-Mean Method Output**

The Rimu specimen's Mean Residual Error started off at 7.37 %, and after two points have been removed it becomes 1.22 %, below the tolerance level.

The  $b$ ,  $t^*$ ,  $k\rho c$ ,  $h$  and  $T_{ig}$  values produced by UCFIRE do not agree with Merryweather's results as shown in Table 35.

Parameter	Merryweather [43]	UCFIRE
$b$ (s <sup>0.5</sup> )	0.050	0.0367
$t^*$ (s)	395	742
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	1.06	1.55
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	18.5	13.8
$h$ (kWm <sup>-2</sup> K)	0.046	0.0405
$T_{ig}$ (K)	695	633

**Table 35: Comparison of Rimu (20 mm) LIFT Ignition Parameters**

The first part of LIFT analysis is to determine the minimum flux by use of the 2 kW/m<sup>2</sup> bracketing method. Essentially this is the average of the first value that causes ignition and the last value that does not cause ignition. Thus the minimum flux for the Rimu specimen should be:

$$\dot{q}_{ig,min}'' = \frac{12.5 + 15}{2} = 13.8 \text{ kW} / \text{m}^2$$

This result indicates that some human error may be present in Merryweather's results, which is understandable considering the LIFT data reduction process is laborious and prone to human error. This problem is part of the impetus to develop an automated method of reducing fire test data to avoid unnecessary human error in the results. This

is also why tests taken from Sumathipala and Monette's work [32] will be used to validate the ZM method.

### 8.3.6 Hardboard (5 mm)

The plot of unscrutinised values of the Thermal Response correlation for Merryweather's Hardboard specimen can be seen in Figure 111, and the plot of scrutinised values can be seen in Figure 112.

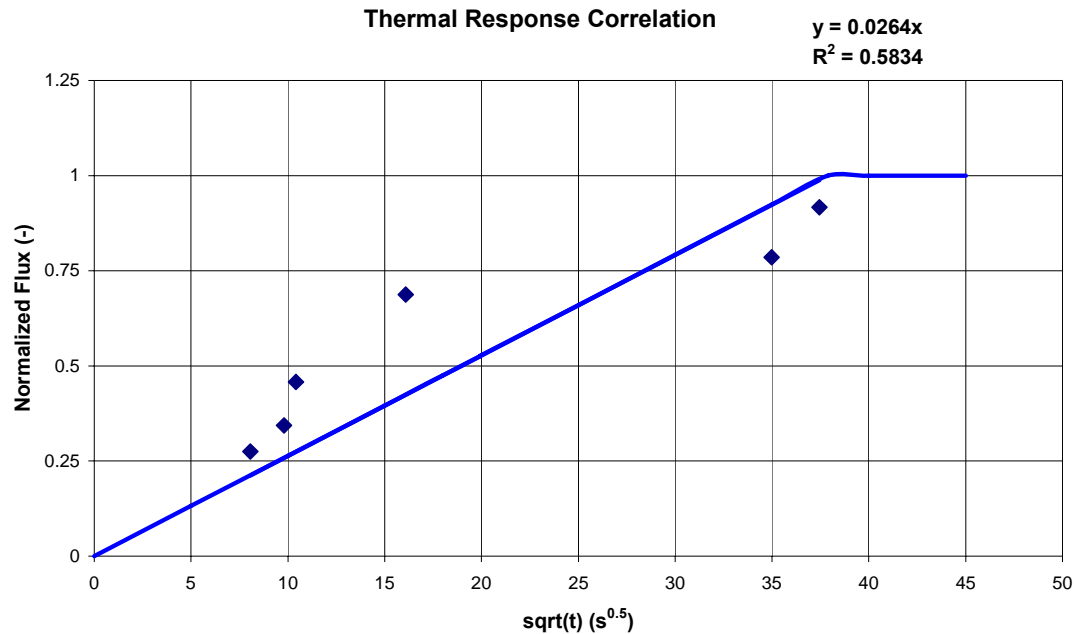


Figure 111: Unscrutinised TR Correlation for Hardboard

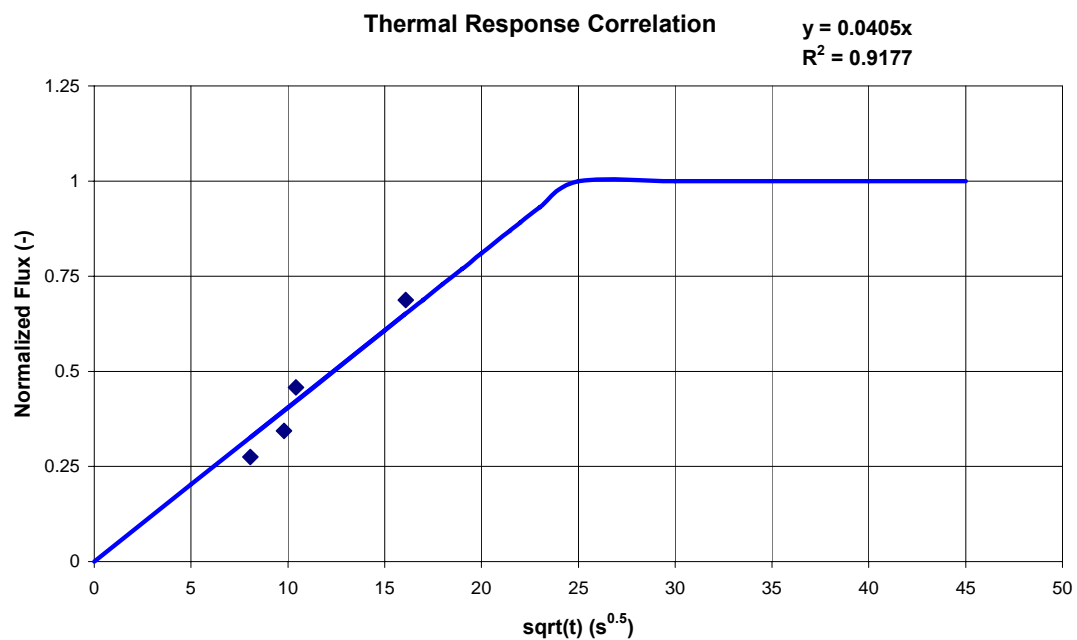


Figure 112: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 36.

Iteration	Mean Residual Error (%)
0	7.17
1	19.1
2*	3.51

**Table 36: Hardboard (5 mm) ZM Method Output**

The Hard Board specimen's Mean Residual Error started off at 7.17 %, and after two points have been removed it becomes 3.51 %, below the tolerance level.

The  $b$ ,  $t^*$ ,  $k\rho c$ ,  $h$  and  $T_{ig}$  values produced by UCFIRE do not agree with Merryweather's results as shown in Table 37.

Parameter	Merryweather [43]	UCFIRE
$b$ (s <sup>0.5</sup> )	0.052	0.0407
$t^*$ (s)	375	604
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	0.88	1.24
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	17.5	13.8
$h$ (kWm <sup>-2</sup> K)	0.043	0.0402
$T_{ig}$ (K)	682	633

**Table 37: Comparison of Hardboard (5 mm) LIFT Ignition Parameters**

The first part of LIFT analysis is to determine the minimum flux by use of the 2 kW/m<sup>2</sup> bracketing method. Essentially this is the average of the first value that causes ignition and the last value that does not cause ignition. Thus the minimum flux for the Hardboard specimen should be:

$$\dot{q}_{ig,min}'' = \frac{12.5 + 15}{2} = 13.8 \text{ kW} / \text{m}^2$$

This result indicates that some human error may be present again in Merryweather's results.

#### **8.4 Sumathipala and Monette's LIFT Ignition Data**

Two LIFT ignition tests were inspected from Sumathipala and Monette's work [32].

These specimens were:

- Gypsum Wallboard (16 mm)
- Plywood (12 mm)

Sumathipala and Monette's Plywood specimen's LIFT ignition data can be seen in Table 38.

Flux (kW/m <sup>2</sup> )	Flux Ratio (-)	Time (s)
50	0.28	9
40	0.35	13
30	0.47	28
20	0.70	150
15	0.93	827
14	1.00	1176

**Table 38: Sumathipala and Monette Plywood Specimen's Ignition Data**

As Table 38 shows Sumathipala and Monette did not test the specimen at a flux that does not cause ignition, thus they have not determined the minimum flux with the 2 kW/m<sup>2</sup> bracketing method. To get this data to work with the UCFIRE DBMS a dummy flux measurement of 14 kW/m<sup>2</sup> was inserted into the data set which will still produce an equivalent minimum flux of 14 kW/m<sup>2</sup>.

### 8.4.1 Gypsum Wallboard (16 mm)

The plot of unscrutinised values of the Thermal Response correlation for Sumathipala and Monette's Gypsum Wallboard specimen can be seen in Figure 113, and the plot of scrutinised values can be seen in Figure 114.

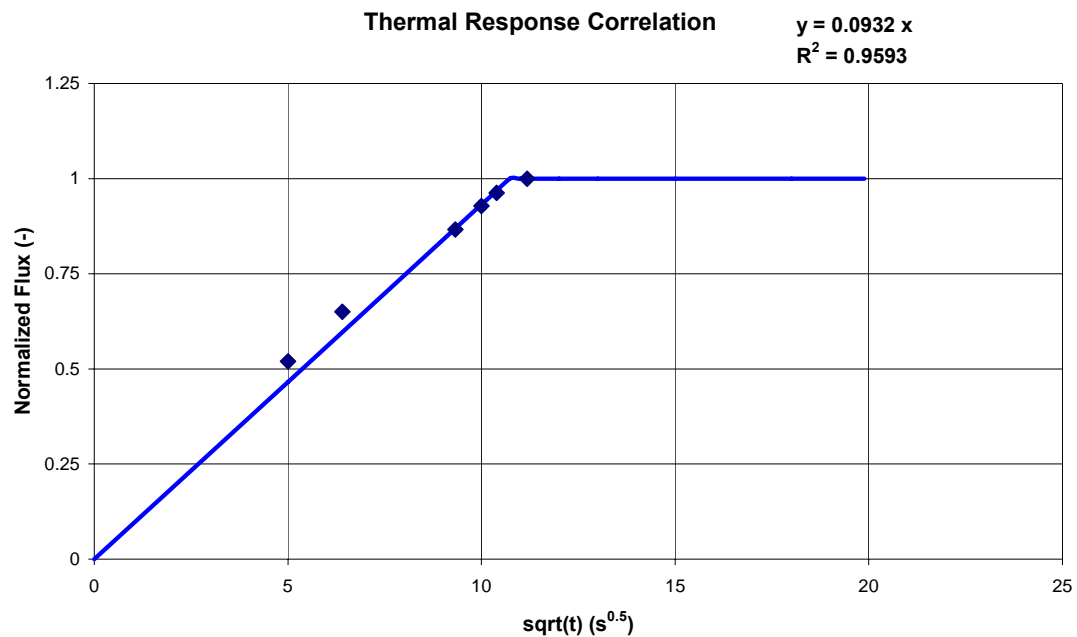


Figure 113: Plot of Unscrutinised TR Correlation for Gypsum Wallboard

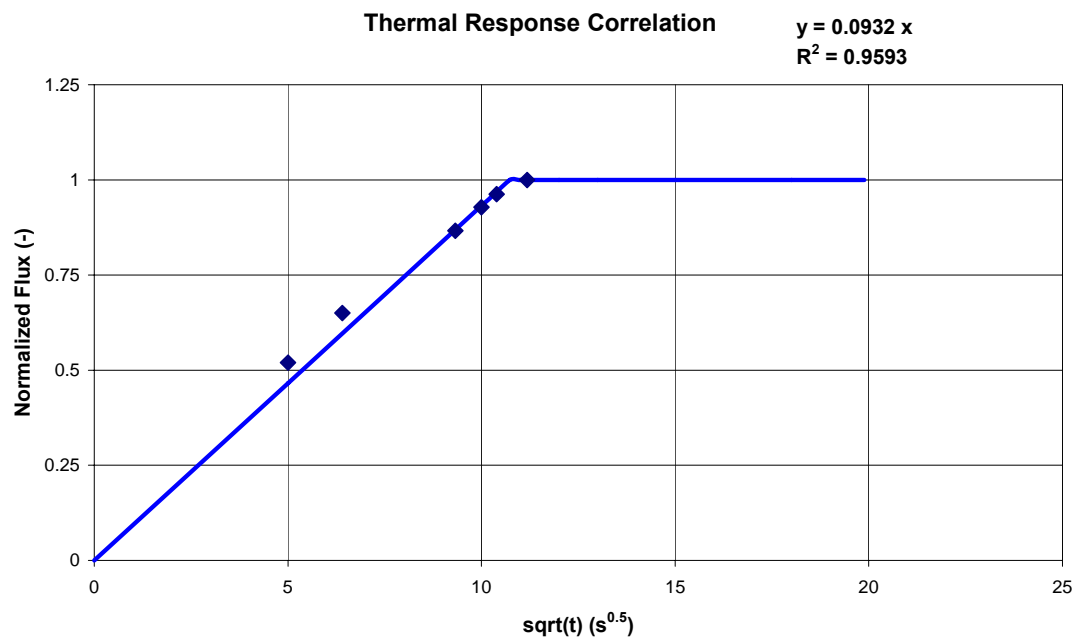


Figure 114: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 39.

Iteration	Mean Residual Error (%)
0*	4.26

**Table 39: Gypsum Wallboard (16 mm) ZM Method Output**

Gypsum Wallboard's Mean Residual Error started off at 4.26 % so no points were needed to be removed. The  $b$ ,  $t^*$ ,  $h$  and  $T_{ig}$  values produced by UCFIRE do agree with Sumathipala and Monette's results as shown in Table 40. However the  $k\rho c$  value produced by UCFIRE does not agree with Sumathipala and Monette's results.

Parameter	Sumathipala and Monette [32]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	26.0	26.0
$b$ (s <sup>0.5</sup> )	0.0932	0.0932
$t^*$ (s)	115	115
$h$ (kWm <sup>-2</sup> K)	0.05293	0.0554
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	3.774	0.450
$T_{ig}$ (K)	746	765

**Table 40: Comparison of Gypsum Wallboard (16 mm) LIFT Ignition Parameters**

Using Sumathipala and Monette's values of  $b$  and  $h$ ; the value of  $k\rho c$  should be:

$$k\rho c = \frac{4}{\pi} \left( \frac{h}{b} \right)^2 = \frac{4}{\pi} \left( \frac{0.05293}{0.0932} \right)^2 = 0.411 \text{ kJ}^2 \text{ m}^{-4} \text{ K}^{-2} \text{ s}^{-1}$$

This value is very similar to the value produced by UCFIRE and greatly dissimilar to the value quoted by Sumathipala and Monette indicating that some human error may be present in Sumathipala and Monette's results.



### 8.4.2 Plywood (12 mm)

The plot of unscrutinised values of the Thermal Response correlation for Sumathipala and Monette's Plywood specimen can be seen in Figure 115, and the plot of scrutinised values can be seen in Figure 116.

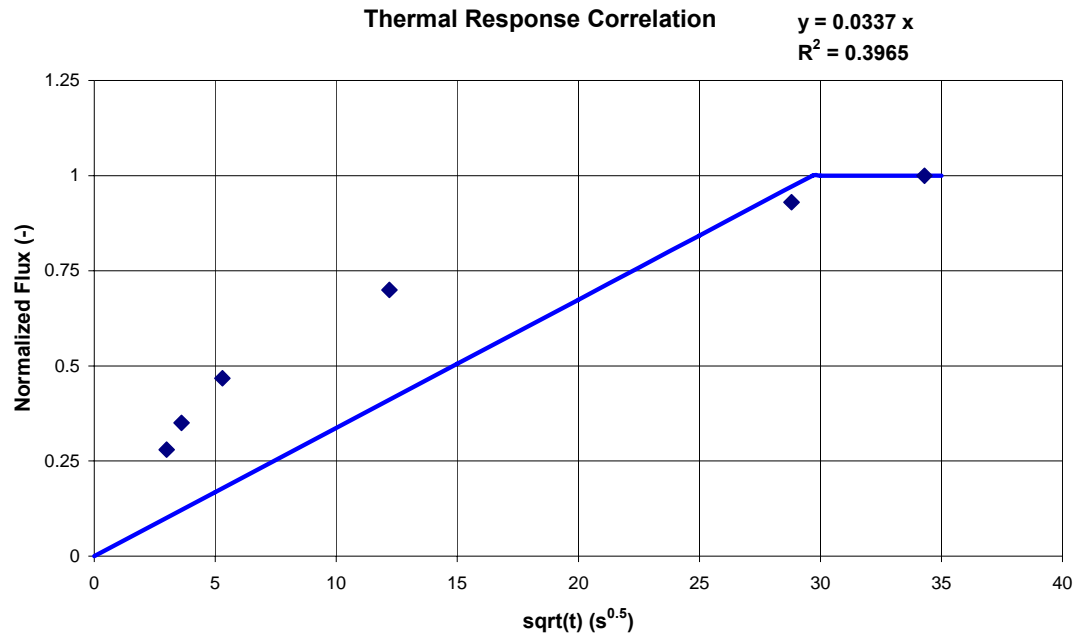


Figure 115: Plot of Unscrutinised TR Correlation for Plywood

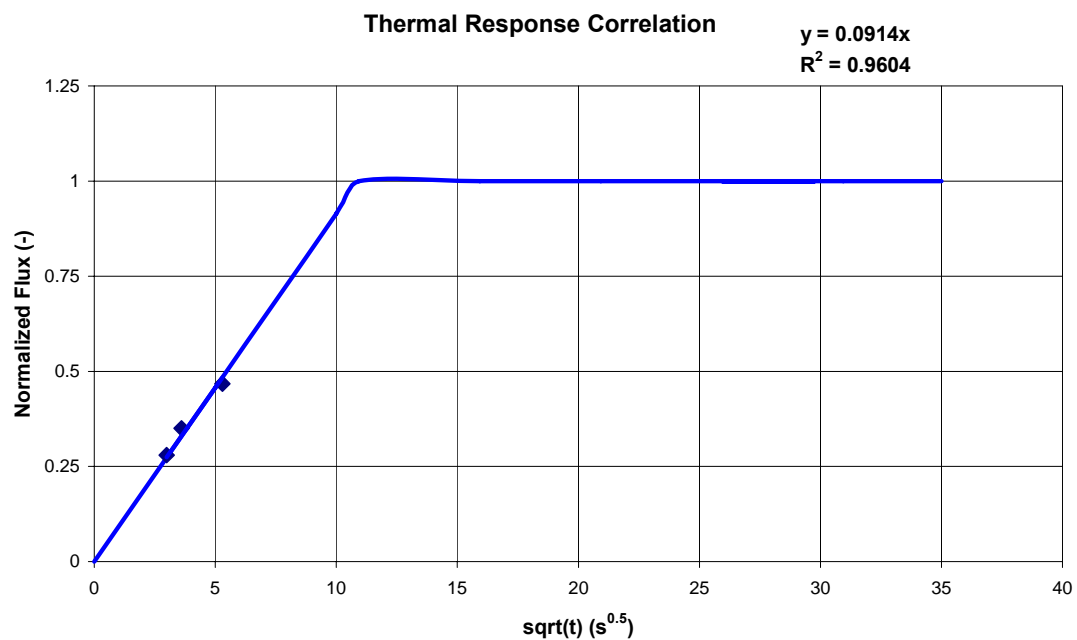


Figure 116: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 41.

Iteration	Mean Residual Error (%)
0	15.4
1	18.7
2	10.5
3*	1.70

**Table 41: Plywood (12 mm) ZM Method Output**

After removing 3 data points the Mean Residual Error reduces below the tolerance level of 5 %.

The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does not agree with Sumathipala and Monette's results as shown in Table 42.

Parameter	Sumathipala and Monette [32]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	14.0	14.0
$b$ (s <sup>0.5</sup> )	0.0337	0.0914
$t^*$ (s)	880	120
$h$ (kWm <sup>-2</sup> K)	0.0408	0.0411
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	1.867	0.257
$T_{ig}$ (K)	636	637

**Table 42: Comparison of Plywood (12 mm) LIFT Ignition Parameters**

It can be clearly seen from Figure 115 that the complete set of data points does not follow the trend of the initial set of data points. Since Sumathipala does not remove any points it is clear that either the dataset has been scrutinised incorrectly or not at all. This provides a good example of what happens when the Thermal Response correlation has not scrutinised; it results in a much lower value for  $b$  and a much higher value for  $t^*$ . These values will then affect any subsequent flame spread tests and analysis.

### **8.5 Babrauskas and Wetterlund's LIFT Ignition Data**

Five LIFT ignition tests were inspected from Babrauskas and Wetterlund's work [34].

These materials are shown in Table 43.

<b>Specimen</b>	<b>Thickness (mm)</b>
FR PU Foam	40
Black PMMA	10
Insulating Fibreboard	13
Cotton/Kevlar/HR PU Foam	50
Acrylic Pile fabric/HR Foam	50

**Table 43: Babrauskas and Wetterlund's LIFT Specimens**

### 8.5.1 FR PU Foam (40 mm)

The plot of unscrutinised values of the Thermal Response correlation for Babrauskas and Wetterlund's FR PU Foam specimen can be seen in Figure 117, and the plot of scrutinised values can be seen in Figure 118.

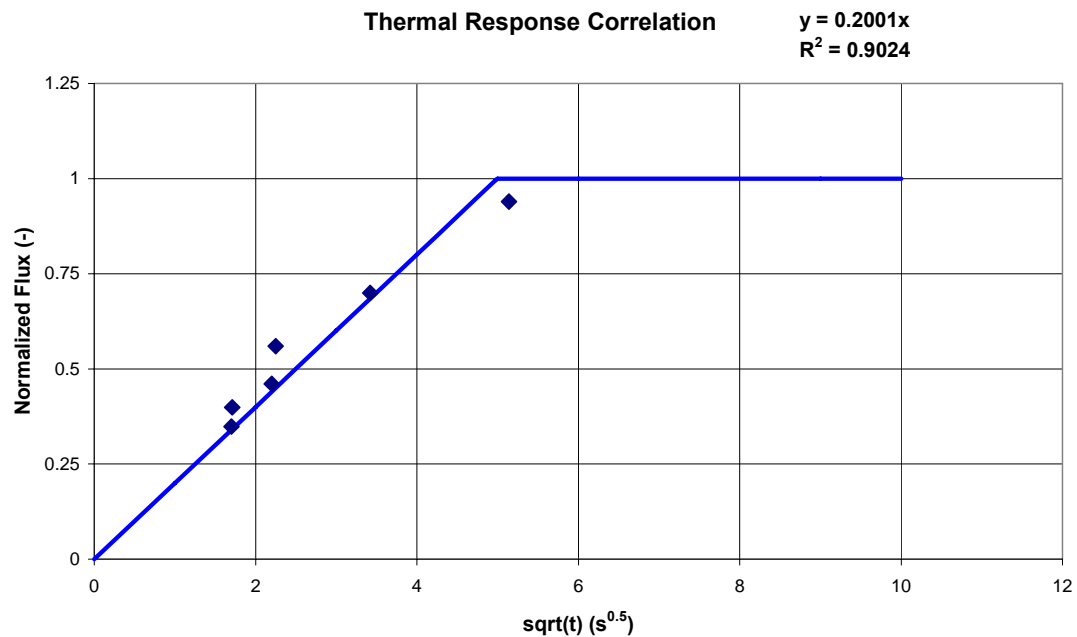


Figure 117: Plot of Unscrutinised TR Correlation for FR PU Foam

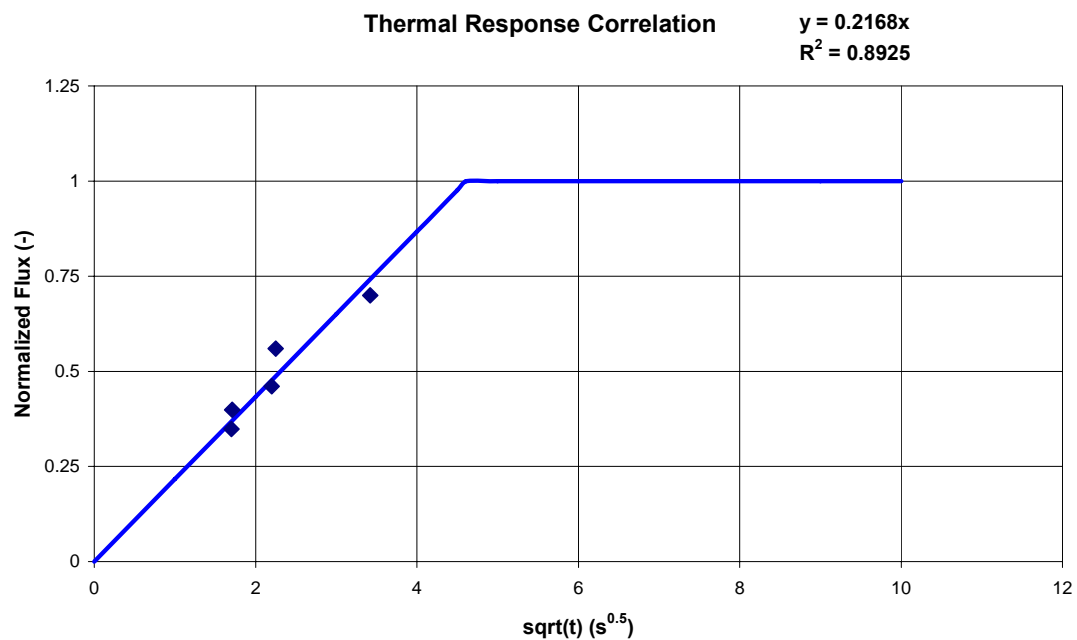


Figure 118: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 44.

Iteration	Mean Residual Error (%)
0	8.67
1*	4.13

**Table 44: FR PU Foam (40 mm) ZM Method Output**

After the removal of one data point FR PU Foam's Mean Residual Error dropped below the tolerance level. The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does agree with Babrauskas and Wetterlund's results as shown in Table 45.

Parameter	Babrauskas and Wetterlund [34]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	14	14
$b$ (s <sup>0.5</sup> )	0.218	0.217
$t^*$ (s)	22	21.2
$h$ (kWm <sup>-2</sup> K)	0.0338	0.0411
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	1.215	0.0457
$T_{ig}$ (K)	653	637

**Table 45: Comparison of PU Foam Specimen (16 mm) LIFT Ignition Parameters**

The Zero-mean method decided to remove one data point and so did Babrauskas and Wetterlund.

### 8.5.2 Black PMMA (10 mm)

The plot of unscrutinised values of the Thermal Response correlation for Babrauskas and Wetterlund's Black PMMA specimen can be seen in Figure 119, and the plot of scrutinised values can be seen in Figure 120.

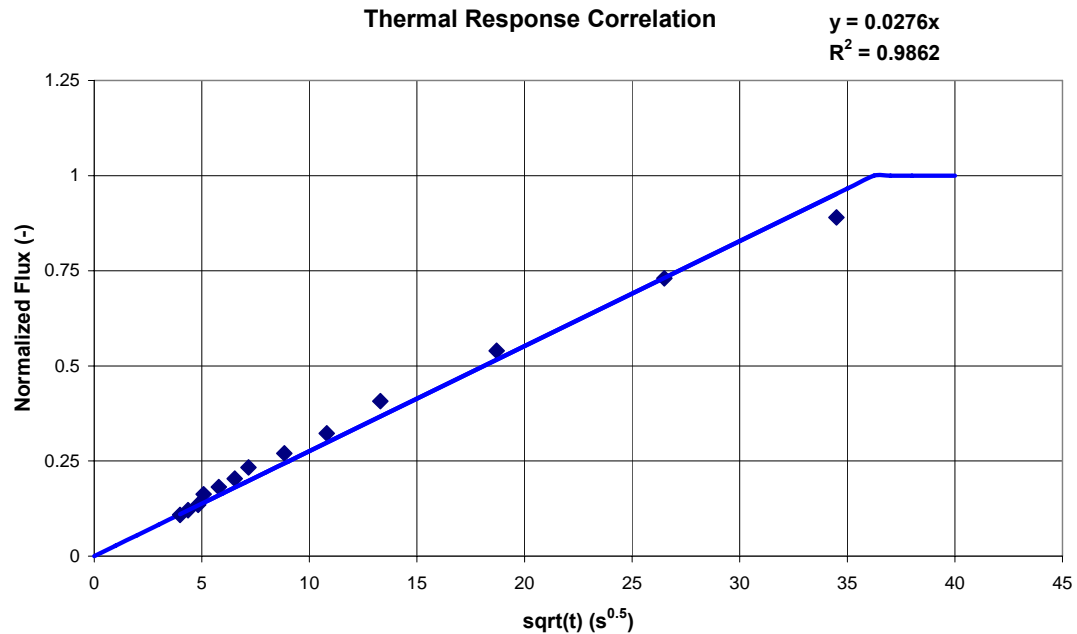


Figure 119: Plot of Unscrutinised TR Correlation for Black PMMA

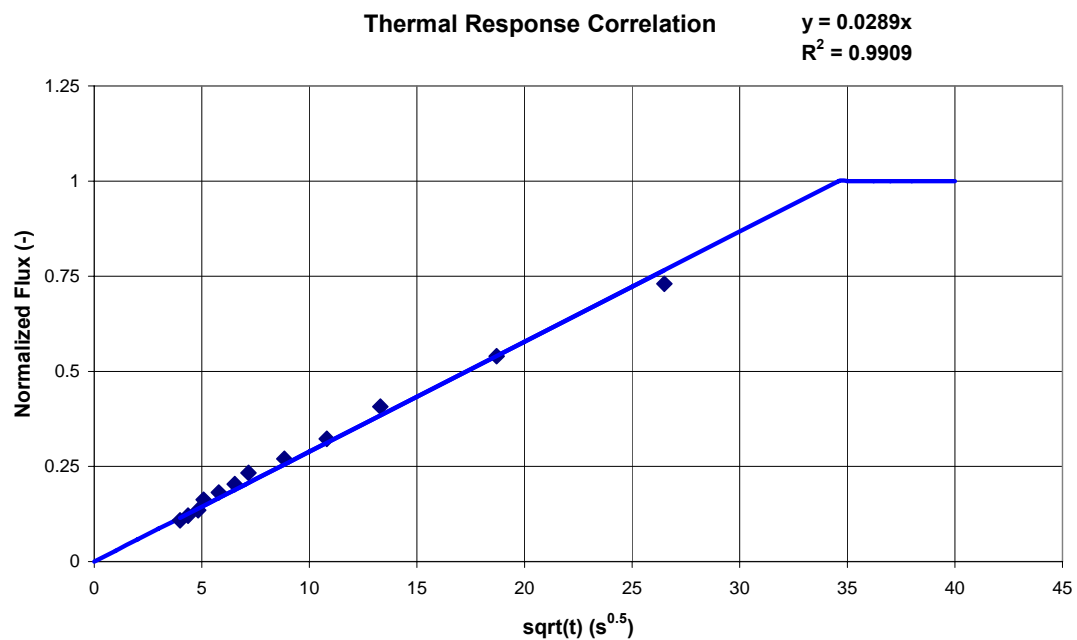


Figure 120: TR Correlation Scrutinised with the ZM Method

The output from the ZM method can be seen in Table 46.

Iteration	Mean Residual Error (%)
0	6.16
1 *	3.54

**Table 46: Black PMMA (10 mm) ZM Method Output**

After the removal of one data point Black PMMA Mean Residual Error dropped below the tolerance level. The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does agree with Babrauskas and Wetterlund's results as shown in Table 47.

Parameter	Babrauskas and Wetterlund [34]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	8	8
$b$ (s <sup>0.5</sup> )	0.0299	0.0277
$t^*$ (s)	1119	1300
$h$ (kWm <sup>-2</sup> K)	0.0308	0.0328
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	1.348	1.79
$T_{ig}$ (K)	556	540

**Table 47: Comparison of Black PMMA (10 mm) LIFT Ignition Parameters**

The Zero-mean method decided to remove one data point but Babrauskas and Wetterlund had a different opinion about the dataset and removed three data points.

### 8.5.3 Insulating Fibreboard (13 mm)

The plot of unscrutinised values of the Thermal Response correlation for Babrauskas and Wetterlund's Insulating Fibreboard specimen can be seen in Figure 121, and the plot of scrutinised values can be seen in Figure 122.

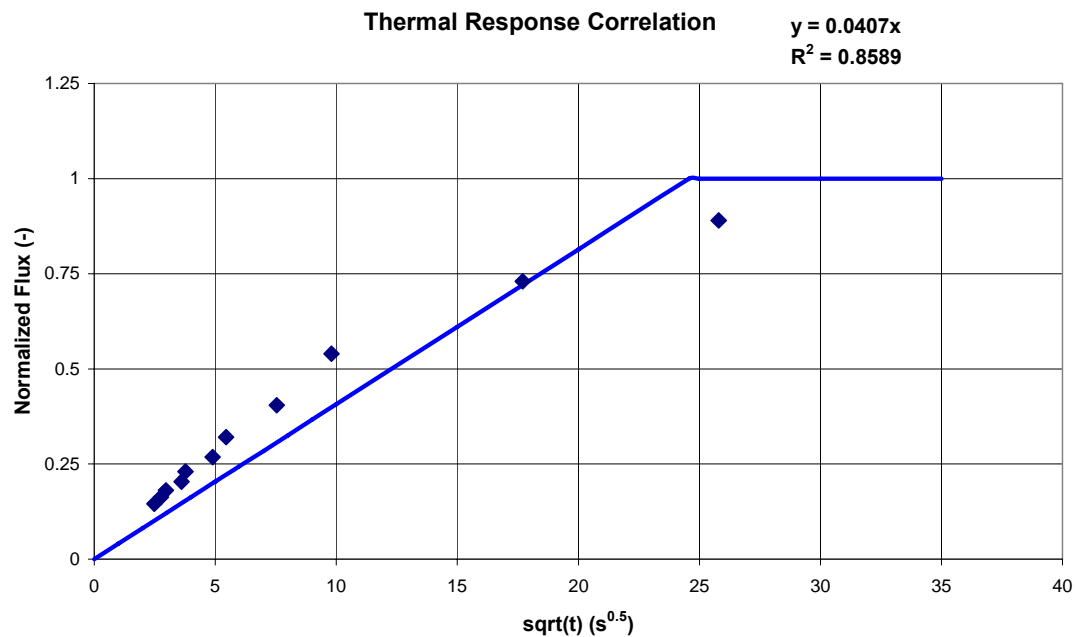


Figure 121: Plot of Unscrutinised TR Correlation for Insulating Fibreboard

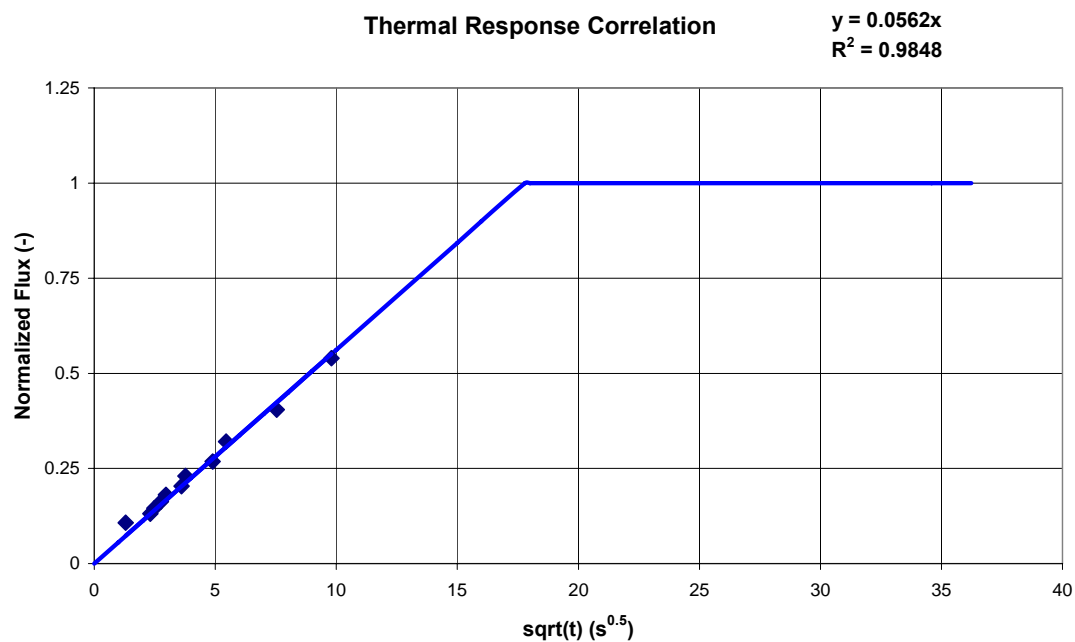


Figure 122: TR Correlation Scrutinised with the ZM Method



The output from the ZM method can be seen in Table 48.

Iteration	Mean Residual Error (%)
0	16.2
1	12.1
2*	1.09

**Table 48: Insulating Fibreboard (13 mm) ZM Method Output**

After the removal of two data points Insulating Fibreboard's Mean Residual Error dropped below the tolerance level. The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does not agree with Babrauskas and Wetterlund's results as shown in Table 49.

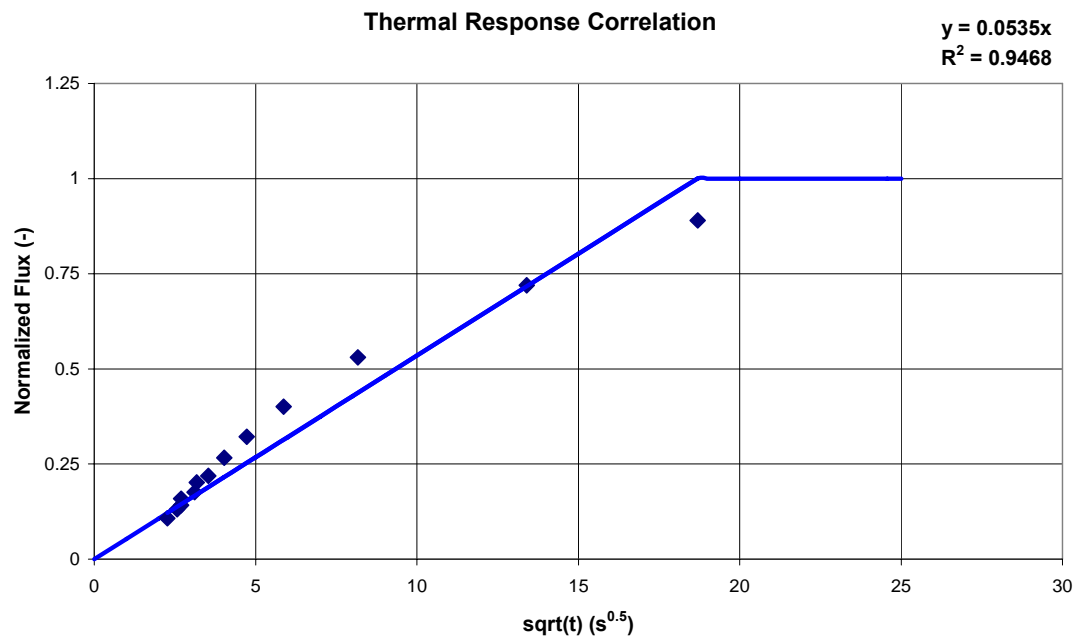
Parameter	Babrauskas and Wetterlund [34]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	8	8
$b$ (s <sup>0.5</sup> )	0.0591	0.0482
$t^*$ (s)	286	430
$h$ (kWm <sup>-2</sup> K)	0.0308	0.0328
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	0.345	0.59
$T_{ig}$ (K)	556	540

**Table 49: Comparison of Insulating Fibreboard (13 mm) LIFT Ignition Parameters**

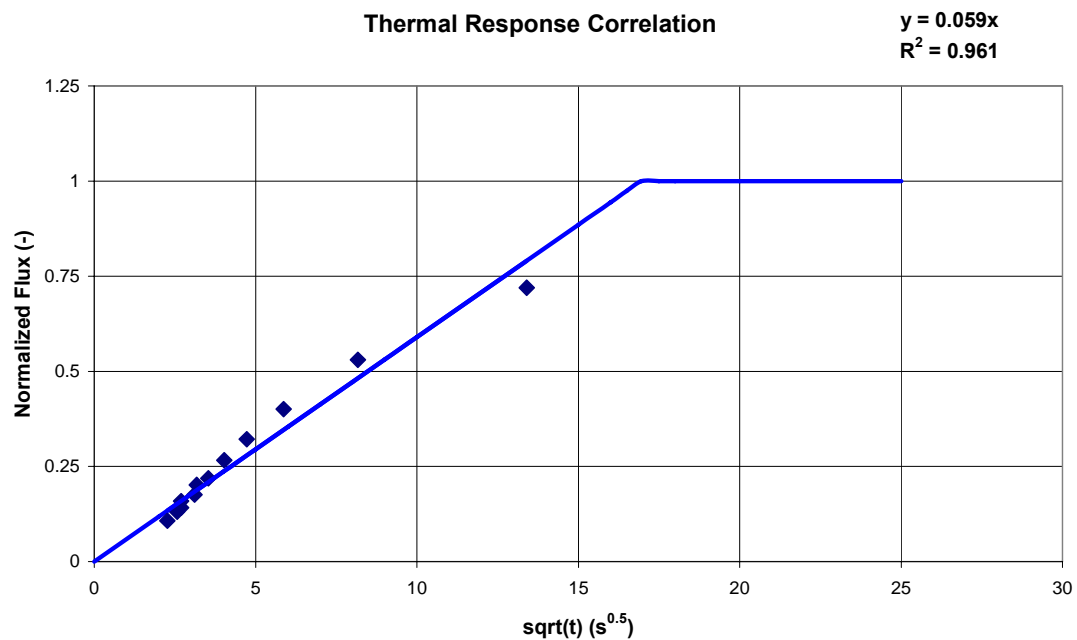
The Zero-mean method decided to remove two data points but Babrauskas and Wetterlund had a different opinion about the dataset and removed six data points.

#### 8.5.4 Cotton/Kevlar/HR PU Foam (50 mm)

The plot of unscrutinised values of the Thermal Response correlation for Babrauskas and Wetterlund's Cotton/Kevlar/HR PU Foam specimen can be seen in Figure 123, and the plot of scrutinised values can be seen in Figure 124.



**Figure 123: Plot of Unscrutinised TR Correlation for Cotton/Kevlar/HR PU Foam**



**Figure 124: TR Correlation Scrutinised with the ZM Method**

The output from the ZM method can be seen in Table 50.

Iteration	Mean Residual Error (%)
0	11.1
1	7.04
2*	0.921

**Table 50: Cotton/Kevlar/HR PU Foam (50 mm) ZM Method Output**

After the removal of one data Cotton/Kevlar/HR PU Foam's Mean Residual Error dropped below the tolerance level. The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does agree with Babrauskas and Wetterlund's results as shown in Table 51.

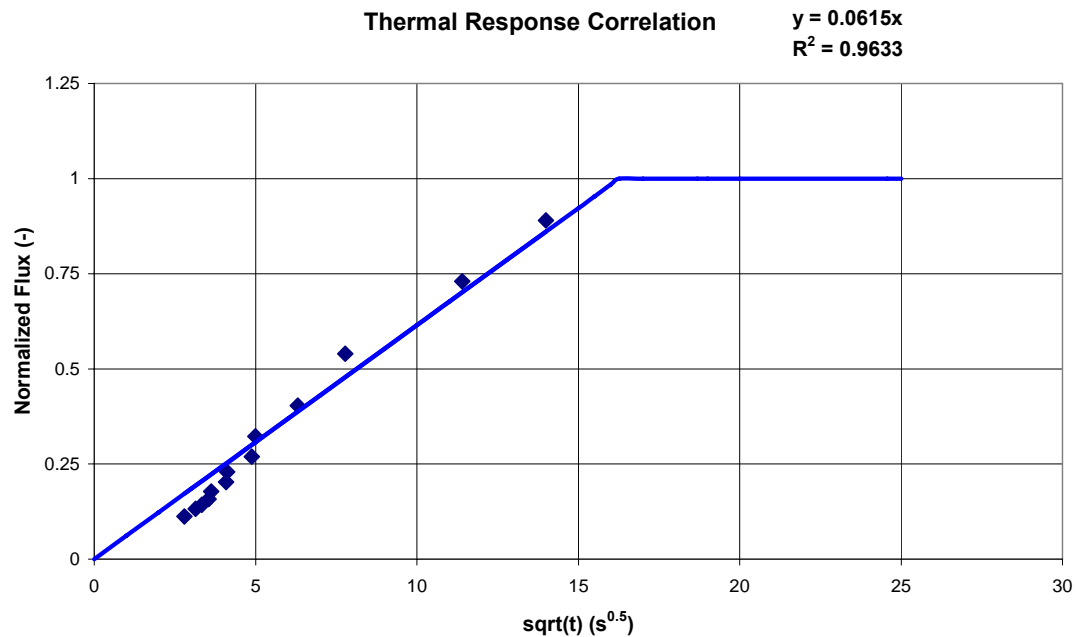
Parameter	Babrauskas and Wetterlund [34]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	7	7
$b$ (s <sup>0.5</sup> )	0.0647	0.0482
$t^*$ (s)	239	430
$h$ (kWm <sup>-2</sup> K)	0.0292	0.0328
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	0.259	0.59
$T_{ig}$ (K)	536	540

**Table 51: Comparison of Cotton/Kevlar/HR PU Foam (50 mm) LIFT Ignition Parameters**

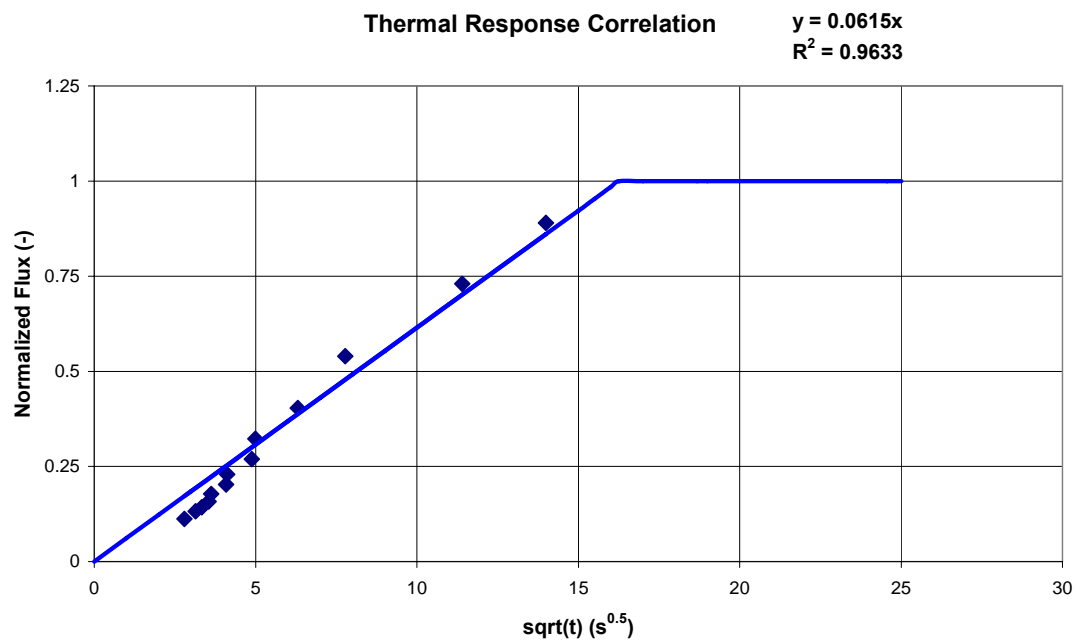
The Zero-mean method decided to remove one data points but Babrauskas and Wetterlund had a different opinion about the dataset and removed two data points.

### 8.5.5 Acrylic Pile Fabric/HR Foam (50 mm)

The plot of unscrutinised values of the Thermal Response correlation for Babrauskas and Wetterlund's Acrylic Pile Fabric/HR Foam specimen can be seen in Figure 125, and the plot of scrutinised values can be seen in Figure 126.



**Figure 125: Plot of Unscrutinised TR Correlation for Acrylic Pile fabric/HR Foam**



**Figure 126: TR Correlation Scrutinised with the ZM Method**

The output from the ZM method can be seen in Table 52.

Iteration	Mean Residual Error (%)
0*	2.89

**Table 52: Acrylic Pile Fabric/HR Foam (50 mm) ZM Method Output**

Acrylic Pile fabric/HR Foam's Mean Residual Error started below the tolerance level so it was not necessary to remove data points. The  $b$ ,  $t^*$ ,  $h$ ,  $k\rho c$  and  $T_{ig}$  values produced by UCFIRE does not agree with Babrauskas and Wetterlund's results as shown in Table 53.

Parameter	Babrauskas and Wetterlund [34]	UCFIRE
$\dot{q}_{ig,min}''$ (kW/m <sup>2</sup> )	7	7
$b$ (s <sup>0.5</sup> )	0.0492	0.0616
$t^*$ (s)	413	264
$h$ (kWm <sup>-2</sup> K)	0.0292	0.0314
$k\rho c$ (kJ <sup>2</sup> m <sup>-4</sup> K <sup>-2</sup> s <sup>-1</sup> )	0.448	0.0311
$T_{ig}$ (K)	536	519

**Table 53: Comparison of Acrylic Pile Fabric/HR Foam (50 mm) LIFT Ignition Parameters**

The Zero-mean method decided not to remove any data points but Babrauskas and Wetterlund had a different opinion about the dataset and removed five data points.

## 8.6 Summary

The ZM algorithm was first applied to Merryweather's MDF specimen to illustrate a case where both the ZM algorithm and the human method decided that it would not be necessary to remove any data points. The LIFT ignition parameters predicted by the ZM algorithm and Merryweather were equivalent.

Merryweather's Plywood and Macrocarpa specimen's Thermal Response correlations both required a single data point to be removed before their ignition parameters agreed with Merryweather's analysis.

The purpose of the ZM algorithm was to provide a mechanistic method of scrutinising the Thermal Response correlation without incurring human error. Merryweather's Hardboard and Rimu specimens' ignition parameters do not agree with that produced using the ZM algorithm. The first part of LIFT analysis involves determining the minimum flux by use of the  $2 \text{ kW/m}^2$  bracketing method. For these two specimens it was discovered that there was human error present in calculating the minimum flux value that the Thermal Response correlation was dependent upon.

The ZM algorithm was then applied to the Sumathipala and Monette's Gypsum Wallboard specimen and it was found that both the ZM algorithm, and Sumathipala and Monette decided that it was not necessary to remove any data points from the Thermal Response correlation. The LIFT ignition parameters predicted by the ZM algorithm, and Sumathipala and Monette were equivalent.

The ZM algorithm was then applied to Sumathipala and Monette's Plywood specimen. It can be clearly seen that the complete set of data points does not follow the trend of the initial set of data points. This provides a good example of what happens when the Thermal Response correlation has not scrutinised; it results in a much lower value for  $b$  and a much higher value for  $t^*$ . These values will then affect any subsequent flame spread tests and analysis.

Since Sumathipala and Monette may have scrutinised the Thermal Response correlations incorrectly or not at all; it was decided to validate the ZM algorithm with LIFT ignition data produced by Babrauskas and Wetterlund.

The ZM algorithm was firstly applied to the Babrauskas and Wetterlund's Acrylic Pile Fabric/HR Foam specimen and it was found that the ZM algorithm and Babrauskas and Wetterlund disagreed on the number of data points that should be removed and this significantly affected the values of the ignition parameters.

For the Insulating Fibreboard and the Cotton/Kevlar/HR PU Foam specimens the ZM algorithm also had a difference in opinion in the number of data points that should be removed from the specimens' Thermal Response Correlations. For the Insulating Fibreboard specimen the ZM algorithm suggested removing two data points but Babrauskas and Wetterlund removed six data points, and for the Cotton/Kevlar/HR PU Foam specimen the ZM algorithm decided to remove one data point but Babrauskas and Wetterlund removed two data points. This difference in opinion resulted in a significant difference in the values of the LIFT ignition parameters.

The ZM algorithm was then applied to Babrauskas and Wetterlund's FR PU Foam and Black PMMA specimens. The ZM algorithm and the human method each removed one data point from the FR PU Foam specimen's Thermal Response correlation. The ZM algorithm decided to remove only one data point from the Black PMMA specimen's Thermal Response correlation while Babrauskas and Wetterlund remove three data points from the correlation. While there was a discrepancy between the number of data points removed from the Black PMMA specimen's Thermal Response correlation both the ZM algorithm and human method produced equivalent values for the LIFT ignition parameters.

## 9 Scrutinizing the LIFT Critical Flux Correlation

Chapter 8 illustrated that as a data point moves towards the minimum heat flux the zero heat loss requirement for a thermally thick solid may be violated. Thus it would be necessary to scrutinise the data either by human intervention or a mechanistic process. It is possible to modify the ZM method so that it can be used to scrutinise the LIFT Critical Flux (CF) correlation.

The modified Zero-Mean method involves:

1. Multiply the tolerance level (5 %) by the maximum value of  $\dot{q}_e''$ . This will be the new tolerance level.
2. Using the principles of linear regression; fit a straight line to all the data points in the Critical Flux correlation.
3. Calculate the Mean Residual Error (MRE).
4. If the Mean Residual Error is significantly greater than zero (i.e. the tolerance level) then either remove the left-most data point or a cluster of values at a single  $\dot{q}_{ig}'' / \dot{q}_e''$  from the left of the plot.
5. Repeat steps 2 - 4 until the Mean Residual Error is less than or equal to the tolerance level.

Some important points to note:

- Since rounding error present in all computer calculations it is unreasonable to expect the Mean Residual Error of the correlation to be exactly zero for a linear set for data so a value of 5% of the maximum value of  $\dot{q}_e''$  was chosen as the stopping point. The significance of this value is that 5 % is considered to be a reasonable amount of error as it is analogous to two standard deviations away from the mean of a normal distribution i.e. the 95 percentile.
- Note for the LIFT Critical Flux correlation data points must be removed from the left hand side of the curve not the right as for the Thermal Response Correlation.
- From the Thermal Response correlation we know that the linear regression line must go through the origin leading to a single solution; however this time



we are less certain as to where the curve should converge. The x-intercept is no longer set to the origin of the graph and it is in fact now equal to the critical heat flux. To prevent converging to unrealistic solution it was necessary to impose the additional criterion that the Zero-mean method halts if the  $R^2$  value starts to degrade. Thus it is necessary to halt the algorithm if the  $R^2$  value stops improving or the Mean Residual Error is 5 % greater than the last iteration.

The full code in Visual Basic.NET to scrutinise the LIFT Critical Heat Flux correlation (CF correlation) can be seen in *Appendix E: ZM Method for CF Correlation* of this thesis.

### **9.1 ZM Method Applied to Merryweather's LIFT Data**

This algorithm was evaluated firstly with some exemplar LIFT ignition test data from Merryweather's LIFT [25] experiments. These experiments include:

- MDF (18 mm).
- Plywood (17 mm).
- Macrocarpa (20 mm).
- Particle Board (20 mm).
- Rimu (20 mm).
- Hardboard (5 mm).

### 9.1.1 MDF (18 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's MDF specimen can be seen in Figure 127, and the plot of scrutinised values can be seen in Figure 128.

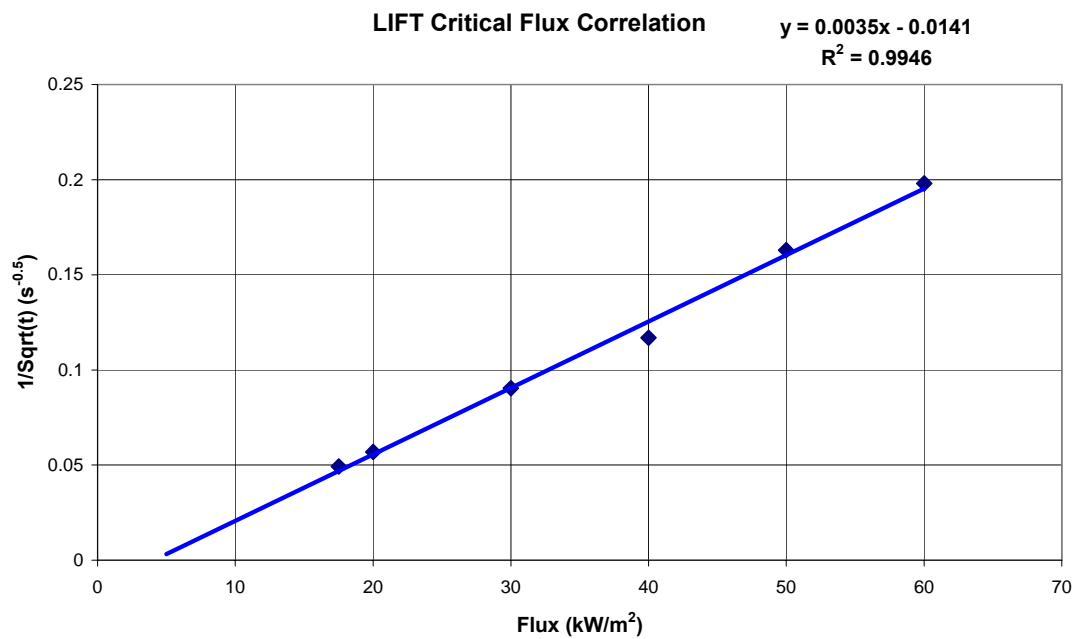


Figure 127: Unscrutinised LIFT Critical Flux Correlation for MDF

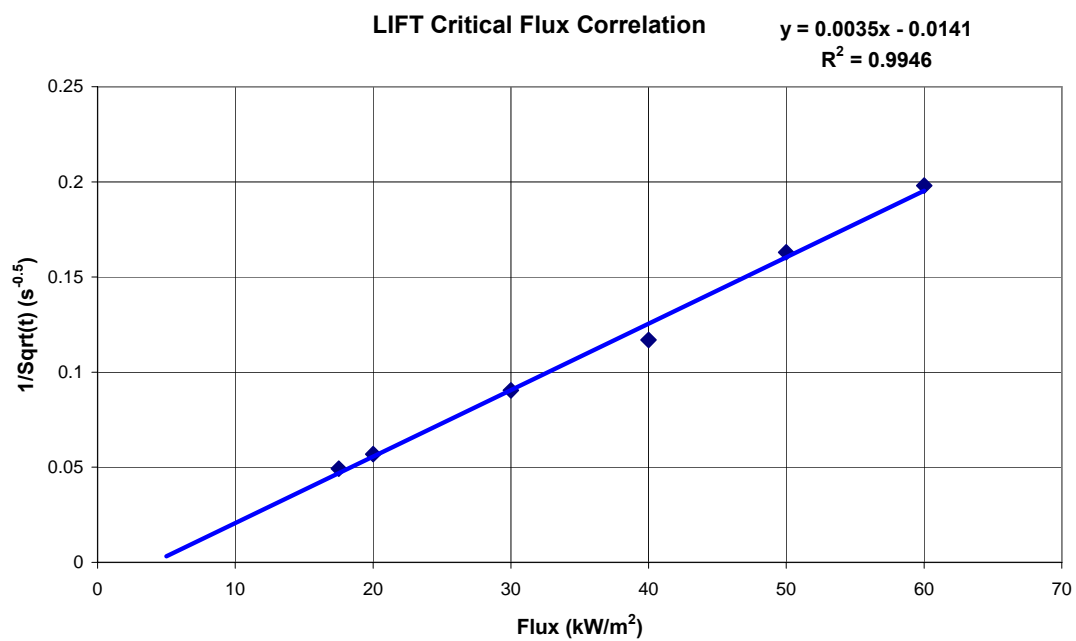


Figure 128: Scrutinised LIFT Critical Flux Correlation for MDF

The output from the modified ZM method can be seen in Table 54.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	1.22	0.995

**Table 54: MDF (18mm) Modified ZM Method Output**

The MDF specimen's Mean Residual Error started off at 1.22% and as this MRE is below the threshold level so there is no need to perform further analysis.

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.0141)}{0.0035} = 4.0 \text{ kW} / \text{m}^2$$

The critical flux value produced by UCFIRE does not agree with Merryweather's results as shown in Table 55.

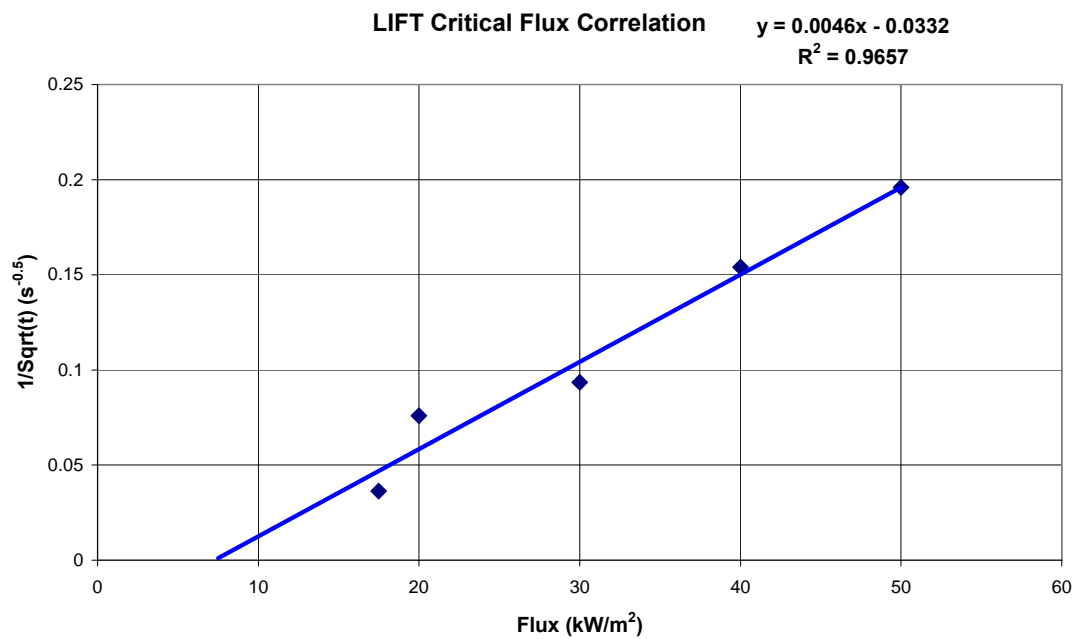
<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	3.4	4.0

**Table 55: MDF (18 mm) Modified ZM Method Output**

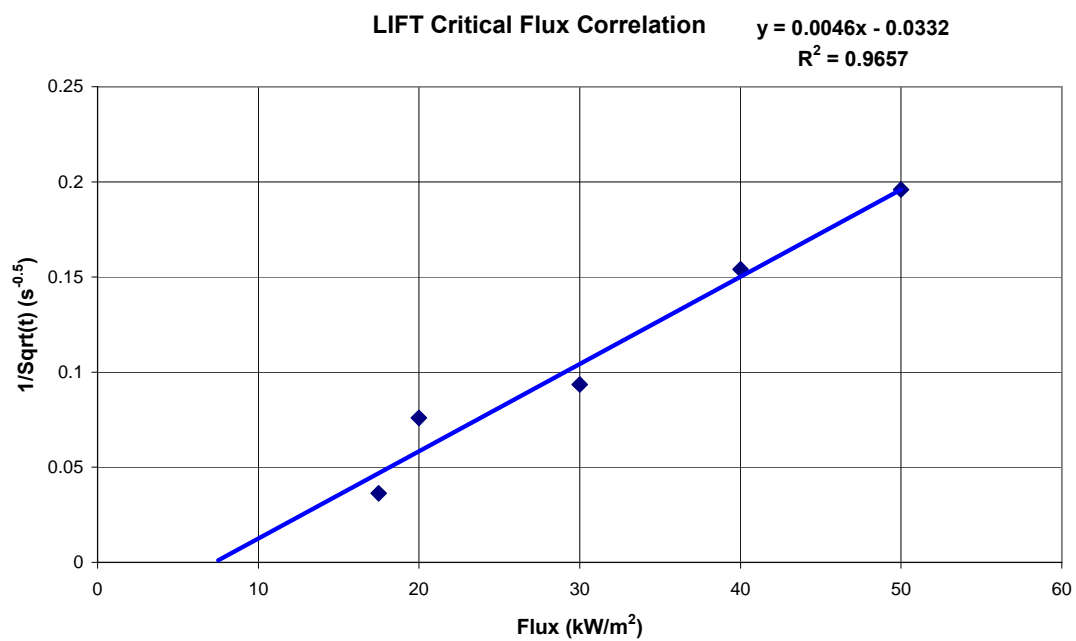
There may be human error involved once again with this value or it may be a difference of opinion. It does not seem necessary to remove a single data point from this correlation but if one were removed it should not impact significantly on the results since the  $R^2$  value is so high.

### 9.1.2 Plywood (17 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's Plywood specimen can be seen in Figure 129, and the plot of scrutinised values can be seen in Figure 130.



**Figure 129: Unscrutinised LIFT Critical Flux Correlation for Plywood**



**Figure 130: Scrutinised LIFT Critical Flux Correlation for Plywood**

The output from the modified ZM method can be seen in Table 56.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	5.46	0.966
1	5.49	0.923

**Table 56: Plywood (17 mm) Modified ZM Method Output**

The Plywood specimen's Mean Residual Error started off at 5.46% and since this is above the tolerance level of 5% the modified ZM method tries to remove one data point but this decreased the  $R^2$  value from 0.966 to 0.923 so the algorithm stopped and took the state of the first iteration.

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.0332)}{0.0046} = 7.2 \text{ kW} / \text{m}^2$$

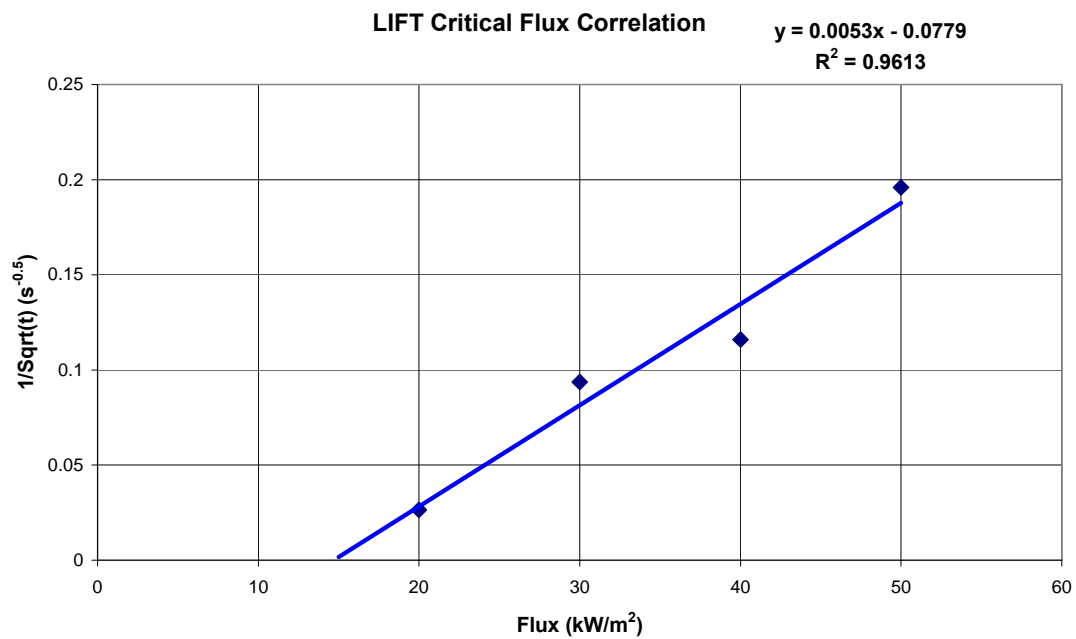
The critical flux value produced by UCFIRE does agree with Merryweather's results as shown in Table 57.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	7.2	7.2

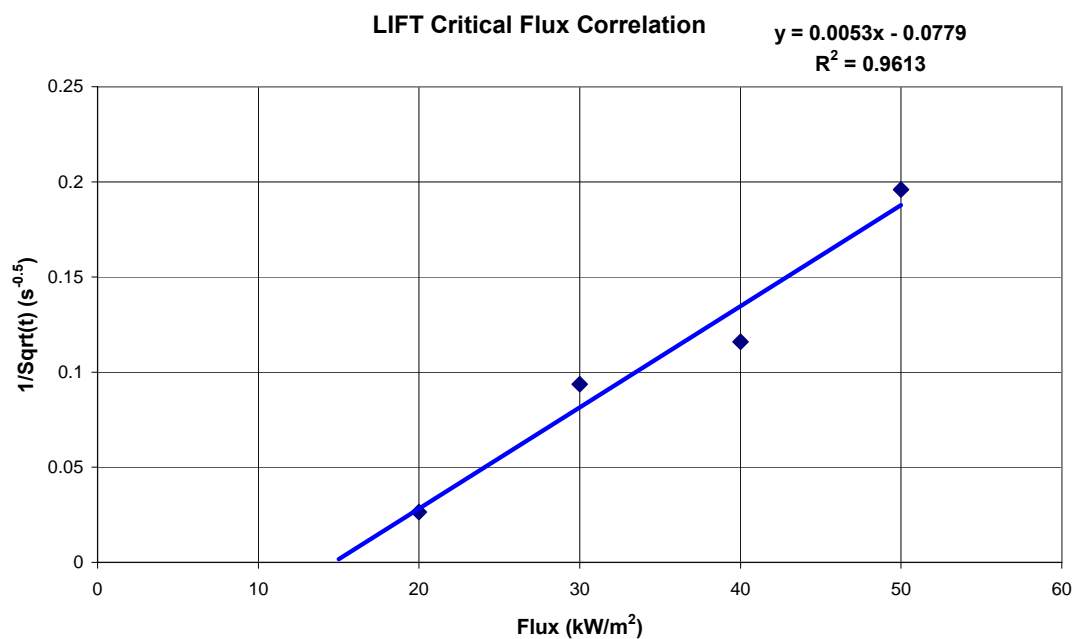
**Table 57: MDF (20 mm) Modified ZM Method Output**

### 9.1.3 Macrocarpa (20 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's Macrocarpa specimen can be seen in Figure 131, and the plot of scrutinised values can be seen in Figure 132.



**Figure 131: Unscrutinised LIFT Critical Flux Correlation for Macrocarpa**



**Figure 132: Scrutinised LIFT Critical Flux Correlation for Macrocarpa**

The output from the modified ZM method can be seen in Table 58.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	1.00	0.961

**Table 58: Macrocarpa (20 mm) ZM Method Output**

The Macrocarpa specimen's Mean Residual Error started off at 1.00 % and since this is below the tolerance level of 5 % the ZM method did not need to remove any data points.

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.0799)}{0.0053} = 15.1 \text{ kW} / \text{m}^2$$

The critical flux value produced by UCFIRE does agree with Merryweather's results as shown in Table 59.

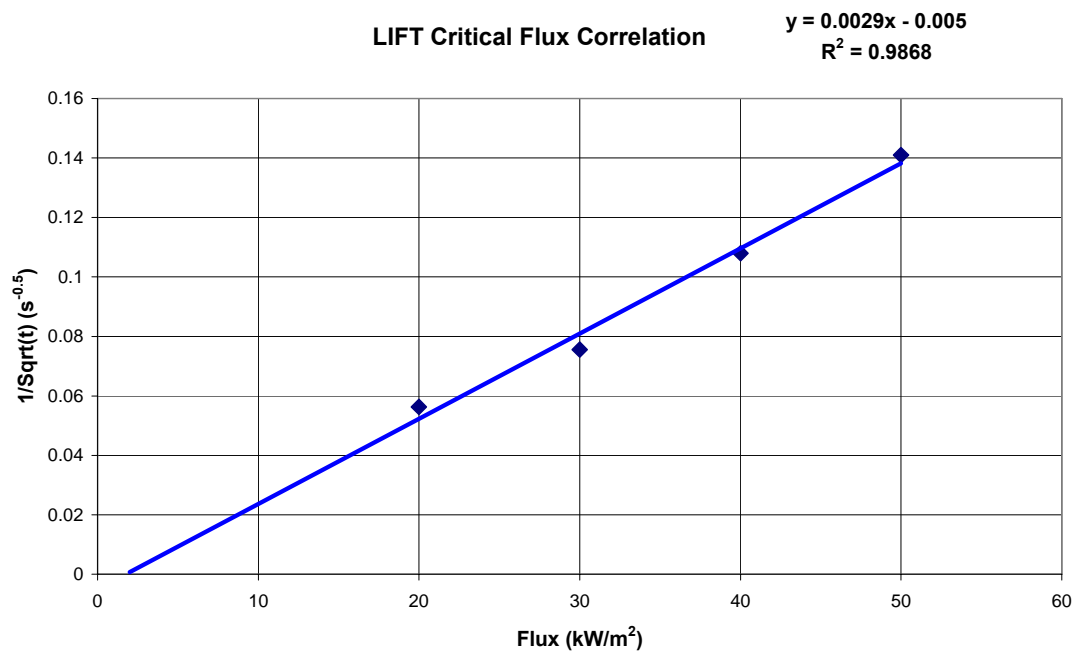
<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	14.7	15.1

**Table 59: Macrocarpa (20 mm) ZM Method Output**

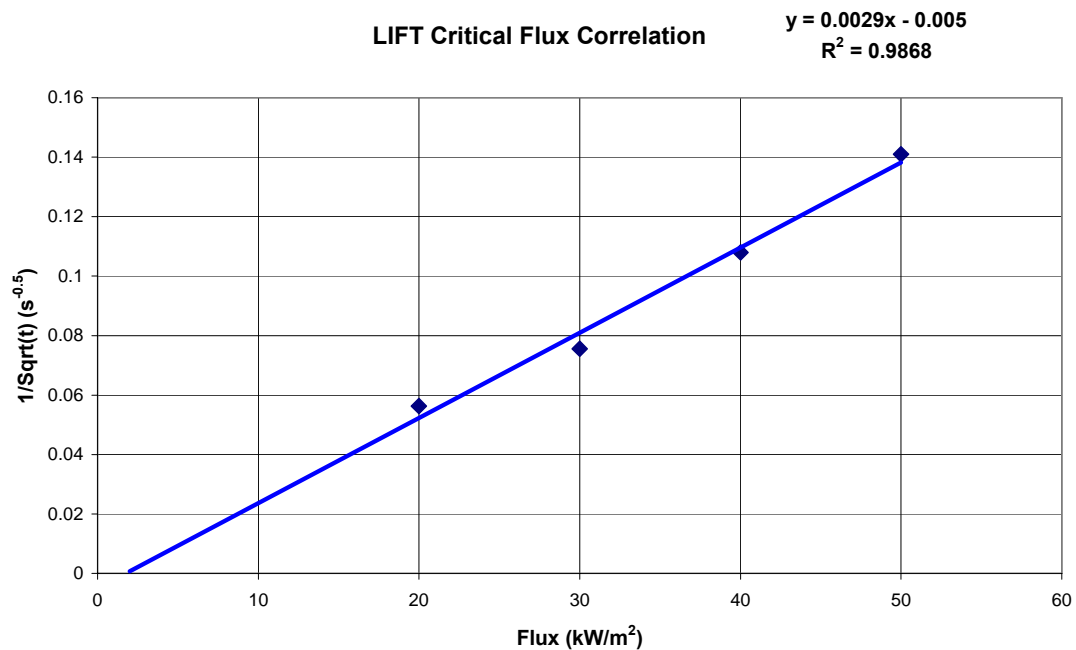
If both these values were rounded to two significant figures then they would be the exactly the same indicating that some minor rounding error is present in the calculations.

### 9.1.4 Particle Board (20 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's Particle Board specimen can be seen in Figure 133, and the plot of scrutinised values can be seen in Figure 134.



**Figure 133: Unscrutinised LIFT Critical Flux Correlation for Particle Board**



**Figure 134: Scrutinised LIFT Critical Flux Correlation for Particle Board**



The output from the modified ZM method can be seen in Table 60.

Parameter	Mean Residual Error (%)	$R^2$ Value
0*	2.87	0.987

**Table 60: Particle Board (20 mm) Modified ZM Method Output**

The Particle Board specimen's Mean Residual Error started off at 2.87 % and since this is below the tolerance level of 5 % the modified ZM method did not need to remove any data points

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.005)}{0.0029} = 1.7 kW / m^2$$

The critical flux value produced by UCFIRE does agree with Merryweather's results as shown in Table 61.

Iteration	Merryweather [43]	UCFIRE
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	1.7	1.7

**Table 61: Particle Board (20 mm) Modified ZM Method Output**

### 9.1.5 Rimu (20 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's Rimu specimen can be seen in Figure 135, and the plot of scrutinised values can be seen in Figure 136.

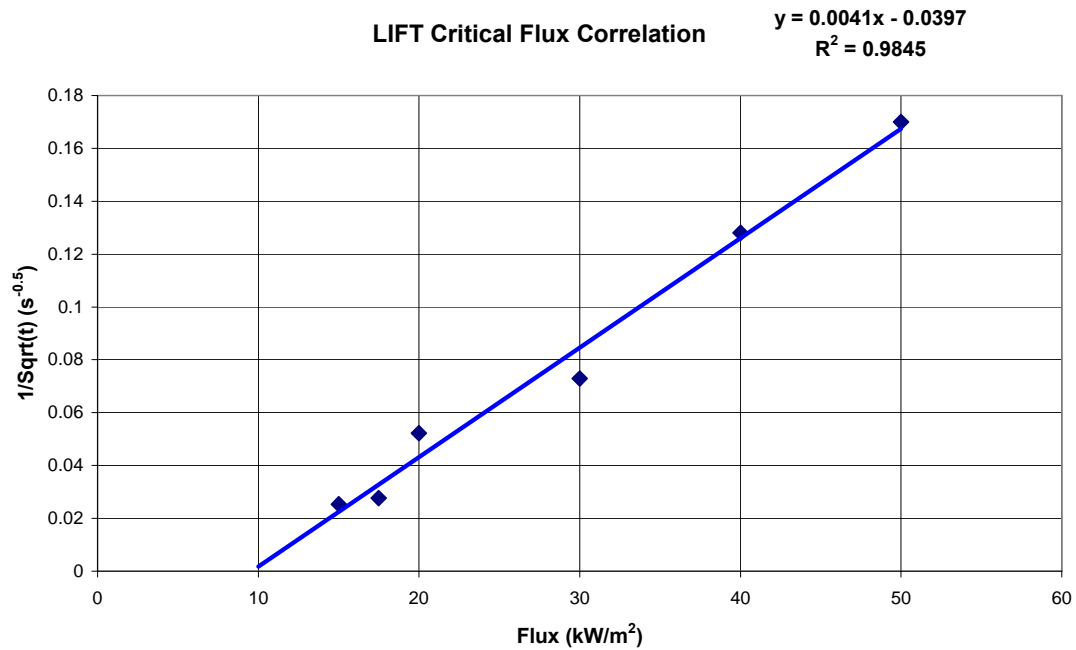


Figure 135: Unscrutinised LIFT Critical Flux Correlation for Rimu

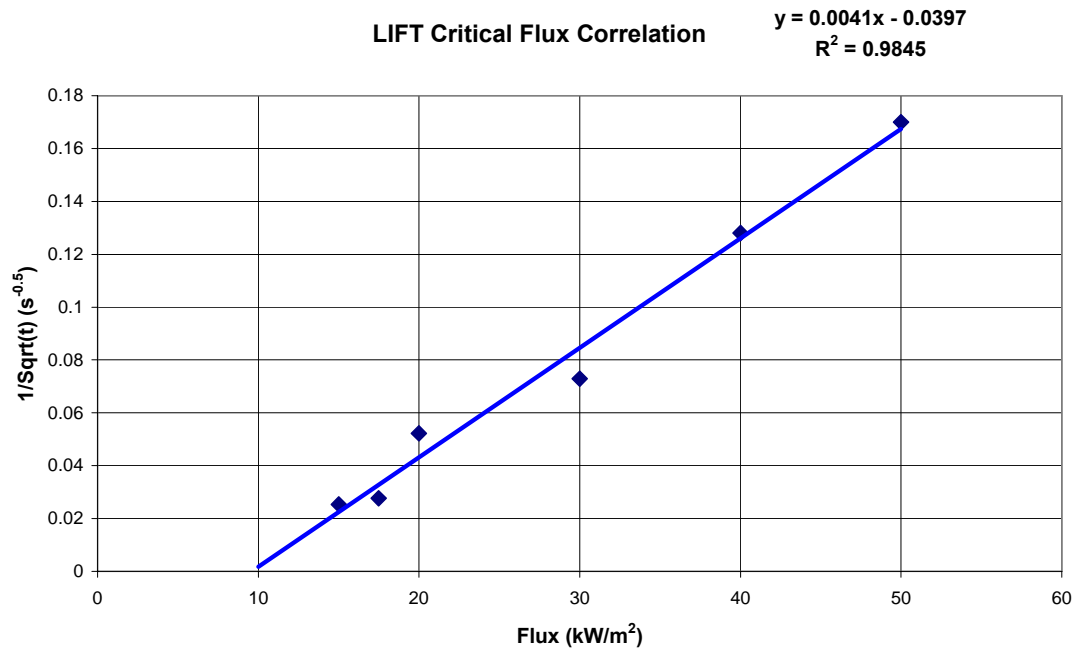


Figure 136: Scrutinised LIFT Critical Flux Correlation for Rimu

The output from the modified ZM method can be seen in Table 62.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	1.74	0.984

**Table 62: Rimu (20mm) Modified ZM Method Output**

The Rimu specimen's Mean Residual Error started off at 1.74 % and since this is below the tolerance level of 5 % the ZM method did not need to remove any data points

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.0397)}{0.0041} = 9.7 \text{ kW} / \text{m}^2$$

The critical flux value produced by UCFIRE does agree with Merryweather's results as shown in Table 63.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	9.6	9.7

**Table 63: Rimu (20 mm) Modified ZM Method Output**

### 9.1.6 Hardboard (5 mm)

The plot of unscrutinised values of the Critical Flux correlation for Merryweather's Hardboard specimen can be seen in Figure 137, and the plot of scrutinised values can be seen in Figure 138.

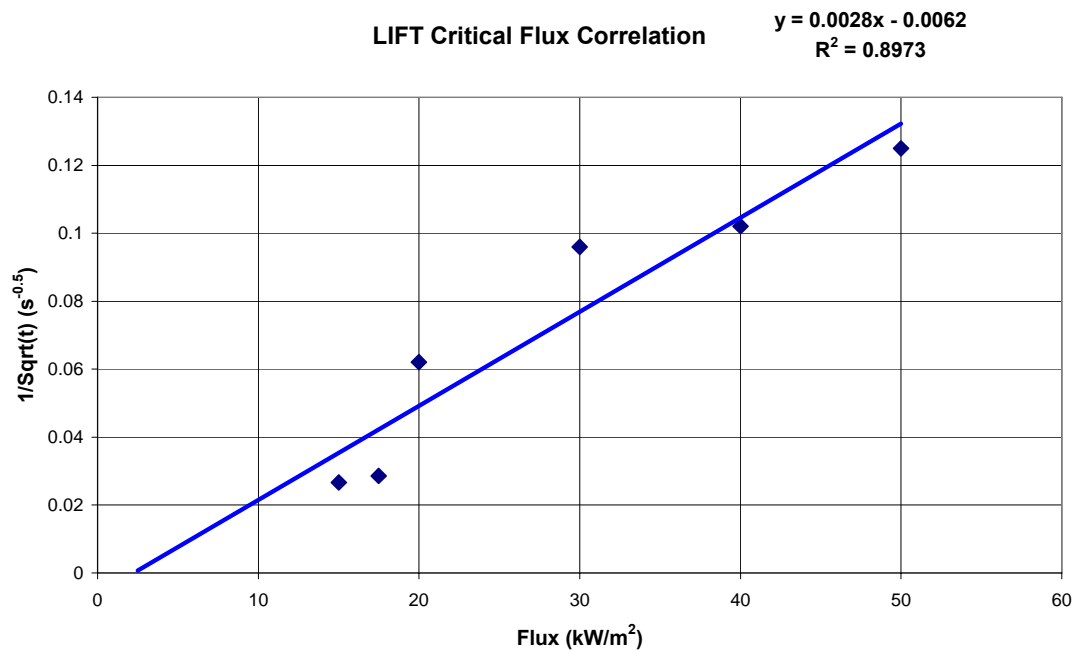


Figure 137: Unscrutinised LIFT Critical Flux Correlation for Hardboard

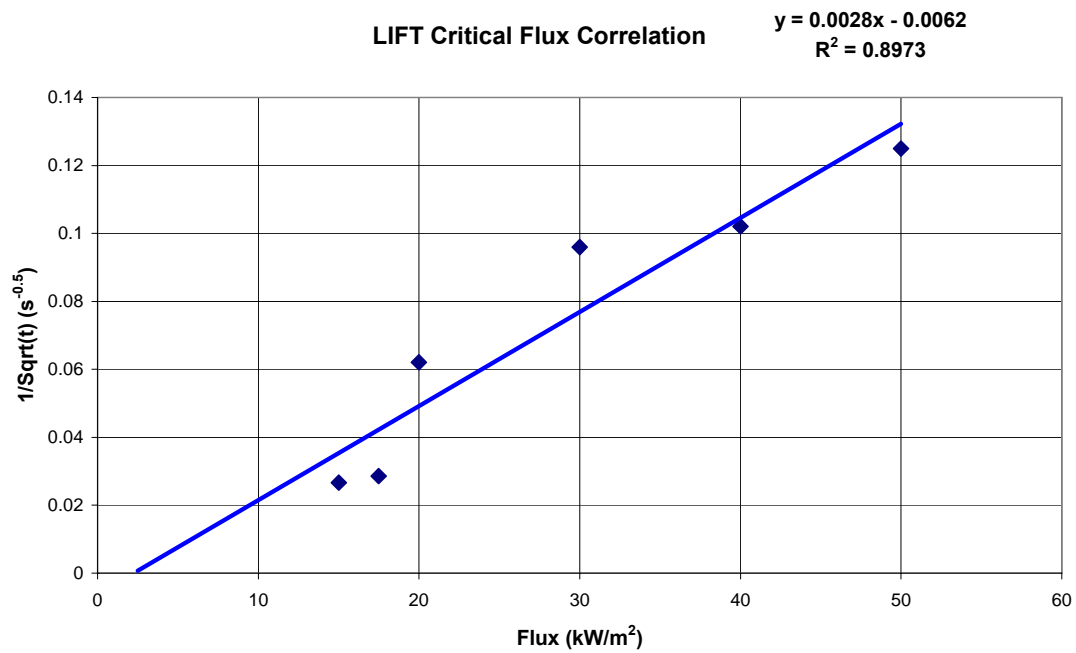


Figure 138: Scrutinised LIFT Critical Flux Correlation for Hardboard

The output from the Modified ZM method can be seen in Table 64.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	6.90	0.897
1	4.79	0.861

**Table 64: Hardboard (5 mm) Modified ZM Method Output**

The Hardboard specimen's Mean Residual Error started off at 6.90 % and since this is above the tolerance level of 5 % the ZM method tried to remove a data point in the next iteration but this decreased the  $R^2$  value so the algorithm stopped and assumed the state of the 0<sup>th</sup> iteration.

The critical flux value is simply the x-intercept which is:

$$\dot{q}_{crit}'' = \frac{-(-0.0062)}{0.0028} = 2.2 \text{ kW} / \text{m}^2$$

The critical flux value produced by UCFIRE does agree with Merryweather's results as shown in Table 65.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$\dot{q}_{crit}''$ (kW/m <sup>2</sup> )	2.2	2.2

**Table 65: Hardboard (5 mm) Modified ZM Method Output**

## **9.2 Summary**

The Critical Flux correlation for six specimen tested by Merryweather were scrutinised with the modified ZM method and it was found that none of the tests required modification. Babrauskas and Wetterlund did not provide critical flux values so it was not possible to criticize their critical flux values.

## 10 Scrutinizing the Flame Spread Correlation

The ASTM standard for the LIFT data reduction (*ASTM E 1321-97a*) [26] requires that a line should be plotted to the linear section of  $V^{-0.5}$  versus  $\dot{q}_{e(x)}'' F(t)$  but unfortunately it does not give guidance on how this should be done. The plot should resemble the one shown in Figure 139.

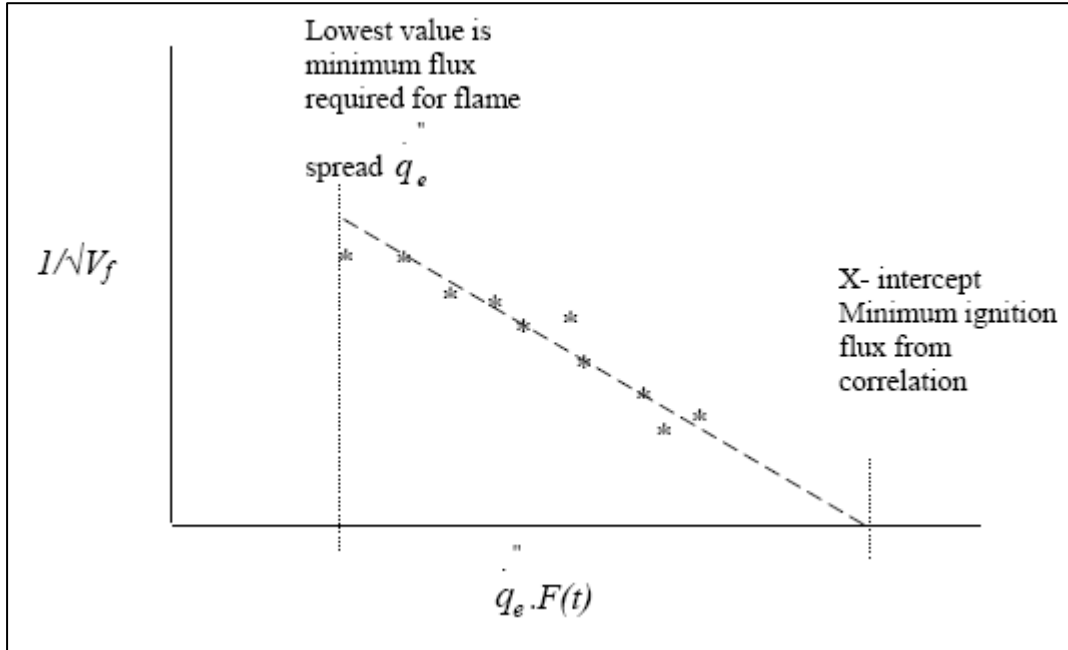


Figure 139: LIFT Flame Spread Correlation [25]

The Flame Spread correlation can be highly nonlinear at both ends of the curves; the flame spread velocity cannot be accurately determined towards the minimum flux and at the other end extinction effects tend to cause some scatter in the data [26].

Since points may need to be removed from either side of the plot the Zero-Mean method had to be modified to scrutinise the Flame Spread correlation.

The modified Zero-Mean method involves:

1. Multiply the tolerance level (5 %) by the maximum value of  $V^{-0.5}$ .
2. Using the principles of linear regression; fit a straight line to all the data points in the flame spread correlation.
3. Calculate the Mean Residual Error.

4. If the Mean Residual Error is significantly greater than zero (i.e. the tolerance level) then remove a single point or cluster of points at a single value of  $\dot{q}_{e(x)}'' F(t)$  from left-hand side of the plot and then the right-hand side of the plot. Calculate the  $R^2$  value for both cases. Select the data set which has the highest  $R^2$  value or take the data points away from both sides of the regression in the case of a tie.
5. Repeat steps 2 - 4 until the Mean Residual Error is less than or equal to the tolerance level, the  $R^2$  value stops improving or the Mean Residual Error is 5% greater than the last iteration.

The full code in VB.NET to scrutinise the LIFT Critical Flux Correlation (CF Correlation) can be seen in *Appendix F: ZM Method for FS Correlation* of this thesis.

### **10.1 ZM Method Applied to Merryweather's LIFT Data**

This algorithm was evaluated firstly with some exemplar LIFT ignition test data from Merryweather's LIFT [25] experiments. These experiments included:

- MDF (18 mm).
- Plywood (17 mm).
- Macrocarpa (20 mm).
- Particle Board (20 mm).
- Rimu (20 mm).
- Hardboard (5 mm).



10.1.1 MDF (18 mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s MDF specimen can be seen in Figure 140, and the plot of scrutinised values can be seen in Figure 141.

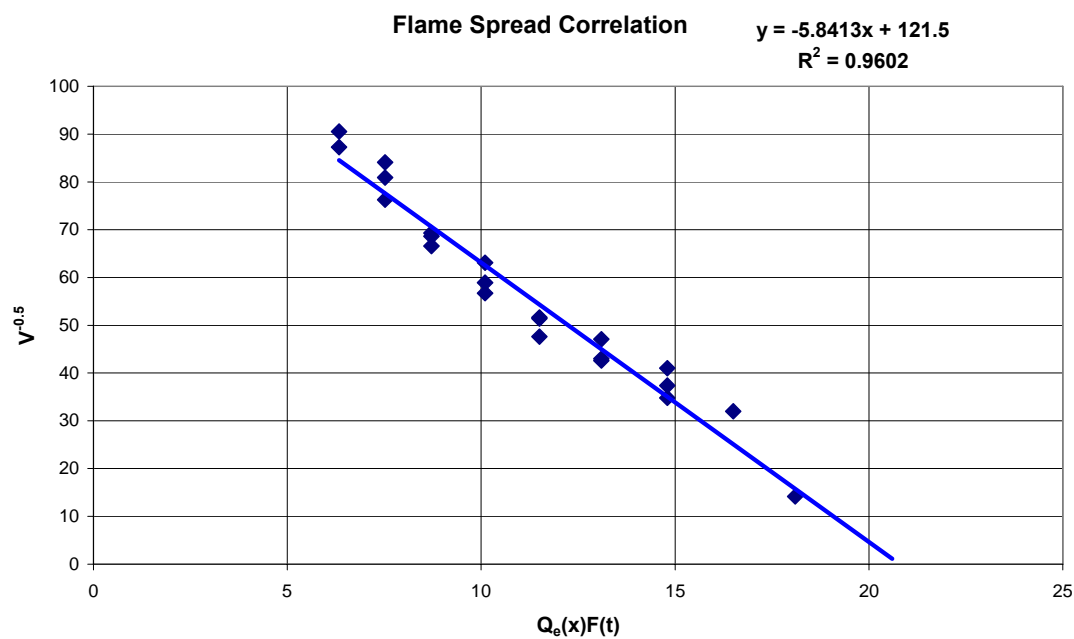


Figure 140: Unscrutinised Flame Spread Correlation for MDF

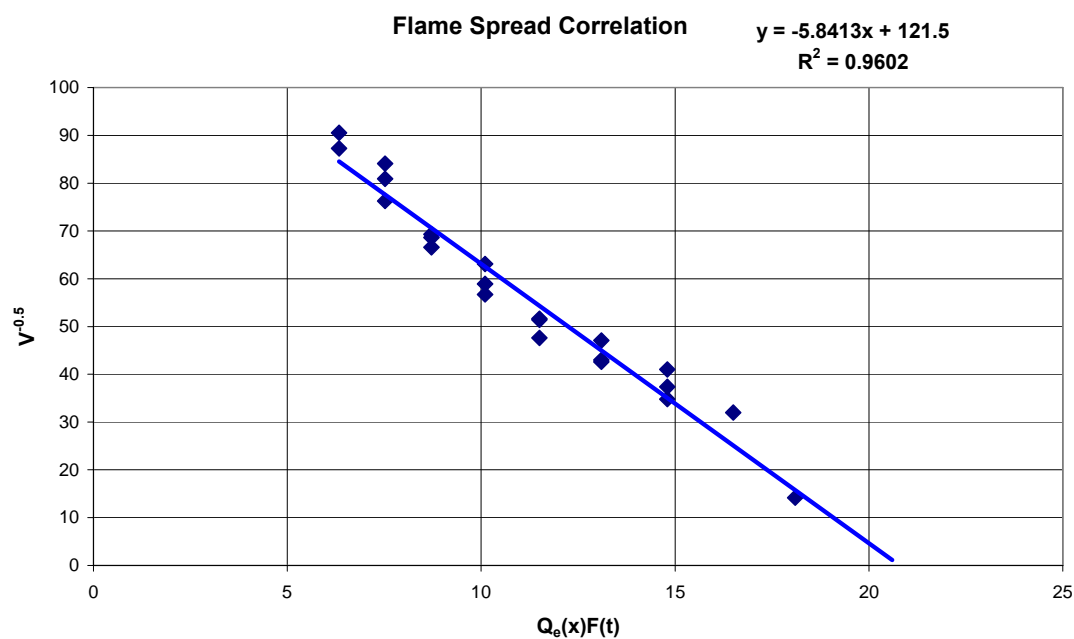


Figure 141: Scrutinised Flame Spread Correlation for MDF

The output from the modified ZM method can be seen in Table 66.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>
0*	1.74	0.960

**Table 66: MDF (18 mm) Modified ZM Method Output**

The MDF specimen's Mean Residual Error started off at 1.74 % and since this is below the tolerance level of 5 % the ZM method did not need to remove any data points.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does not agree with Merryweather's results shown in Table 67.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$C \text{ (s}^{1/2}\text{m}^{3/2}\text{kW}^{-1}\text{)}$	4.0	5.84

**Table 67: MDF (18 mm) Modified ZM Method Output**

As seen from the graph there should be little need to remove data points since the  $R^2$  value is very high. This result may indicate that there was some human error present in Merryweather's intermediate calculations for the Flame Spread correlation. This is why some further exemplar published flame spread data will also be examined to prove the efficacy of the LIFT reduction algorithms and the ZM method.

10.1.2 Plywood (17 mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s Plywood specimen can be seen in Figure 142, and the plot of scrutinised values can be seen in Figure 143.

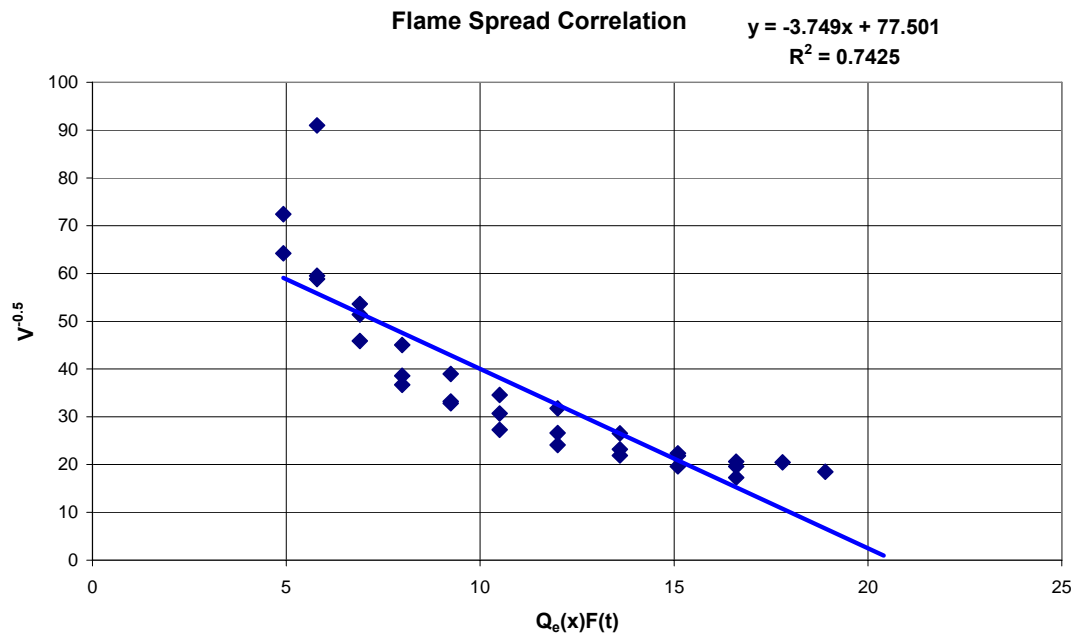


Figure 142: Unscrutinised Flame Spread Correlation for Plywood

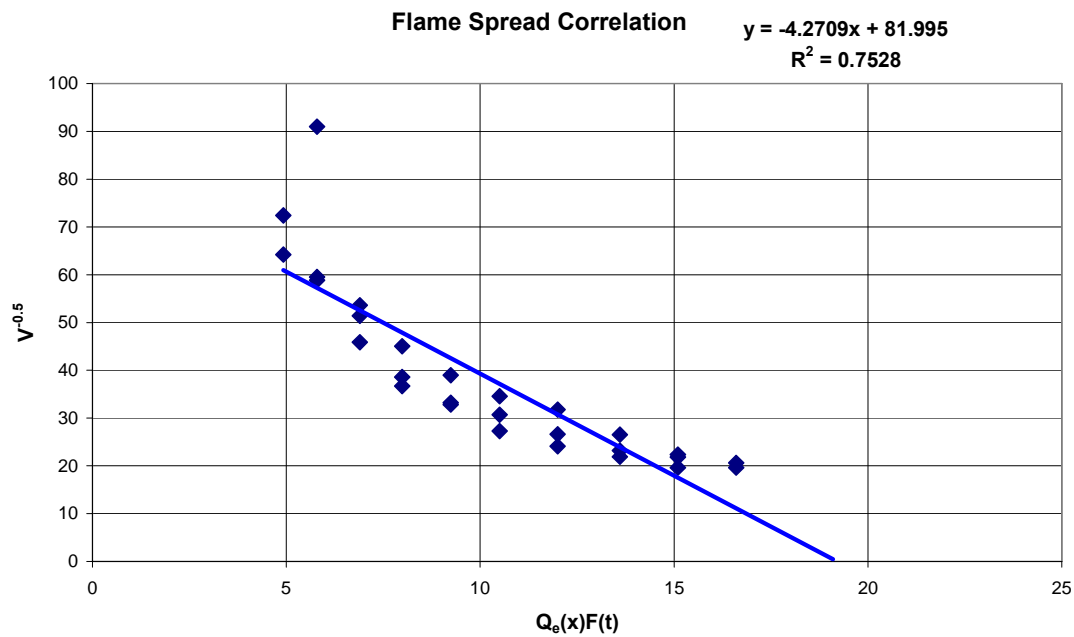


Figure 143: Scrutinised Flame Spread Correlation for Plywood

The output from the Modified ZM method can be seen in Table 68.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0	13.0	0.960	-
1	12.8	0.751	Right-side
2*	5.94	0.761	Right-side
3	5.71	0.759	Right-side

**Table 68: Plywood (17 mm) Modified ZM Method Output**

The Plywood specimen's Mean Residual Error started off at 13.0 % and since this is above the tolerance level of 5 % the ZM methods starts by removing data points from both sides of the curve. The ZM method decided that it would be best to remove data points from the right hand side 3 times until the  $R^2$  decreased on the 4<sup>th</sup> time that data points were removed. The final Mean Residual Error was 5.71 %.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE is reasonably close to Merryweather's results shown in Table 69.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$C \text{ (s}^{1/2} \text{m}^{3/2} \text{kW}^{-1} \text{)}$	3.7	4.27

**Table 69: Plywood (17 mm) ZM Method Output**

10.1.3 Macrocarpa (20 mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s Macrocarpa specimen can be seen in Figure 144, and the plot of scrutinised values can be seen in Figure 145.

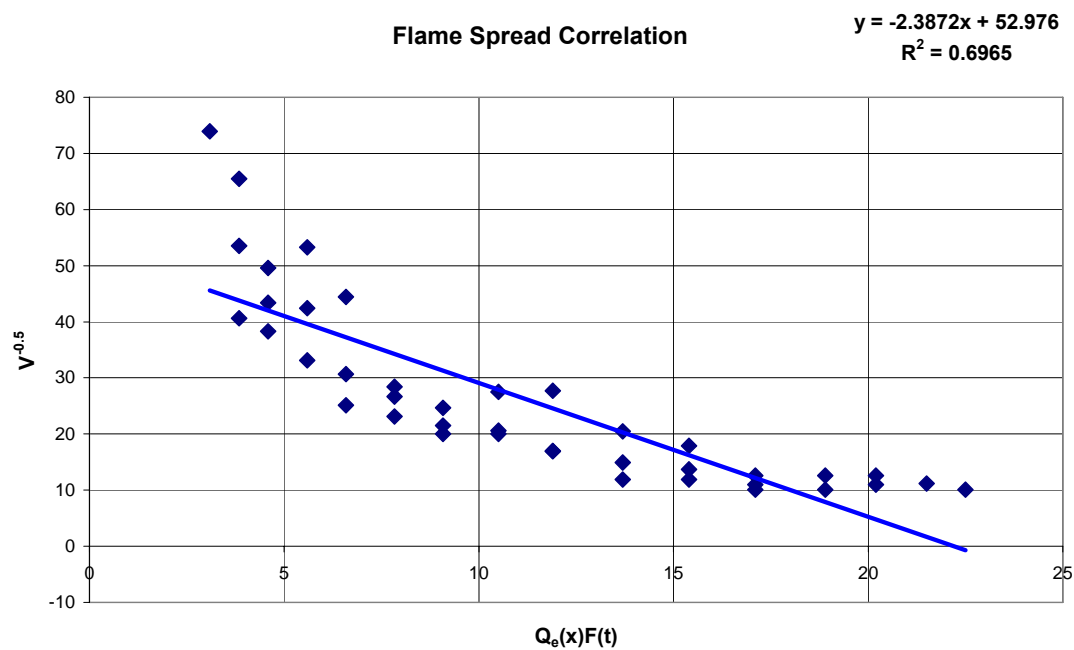


Figure 144: Unscrutinised Flame Spread Correlation for Macrocarpa

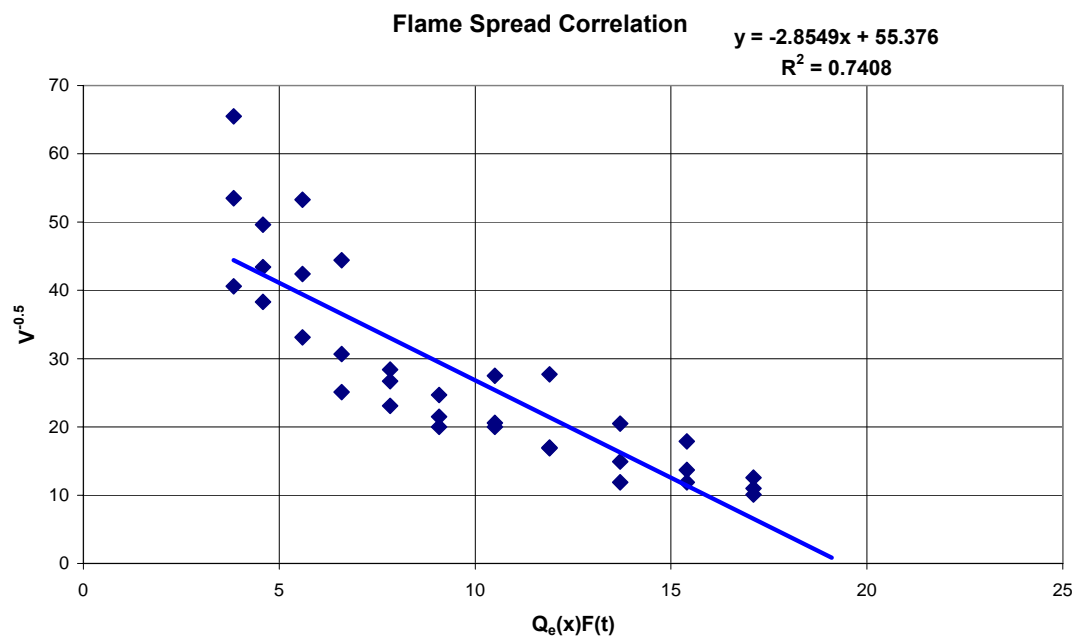


Figure 145: Scrutinised Flame Spread Correlation for Macrocarpa

The output from the Modified ZM method can be seen in Table 70.

Iteration	Mean Residual Error (%)	$R^2$ Value	Side
0	14.7	0.697	-
1	12.7	0.717	LEFT
2	13.0	0.722	RIGHT
3	10.4	0.728	RIGHT
4	8.29	0.739	RIGHT
5*	6.01	0.741	RIGHT
6	3.99	0.739	LEFT

**Table 70: Macrocarpa (20 mm) Modified Zero-Mean Method Output**

The Macrocarpa Specimen's Mean Residual Error started off at 14.7 % and since this is above the tolerance level of 5 % the ZM methods starts to remove data points from both sides of the correlation. The ZM method decided that it would be best to remove one cluster of data points from the Left Hand Side (LHS) and 4 from the Right Hand Side (RHS). The ZM method then tried to remove one more cluster of data points from the LHS but this resulted in a decrease in the  $R^2$  value, stopping the algorithm from progressing.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does agree with Merryweather's results shown in Table 71.

Parameter	Merryweather [43]	UCFIRE
$C$ ( $s^{1/2}m^{3/2}kW^{-1}$ )	2.5	2.85

**Table 71: Macrocarpa (20 mm) Modified ZM Method Output**

10.1.4 Particle Board (20 mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s Particle Board specimen can be seen in Figure 146, and the plot of scrutinised values can be seen in Figure 147.

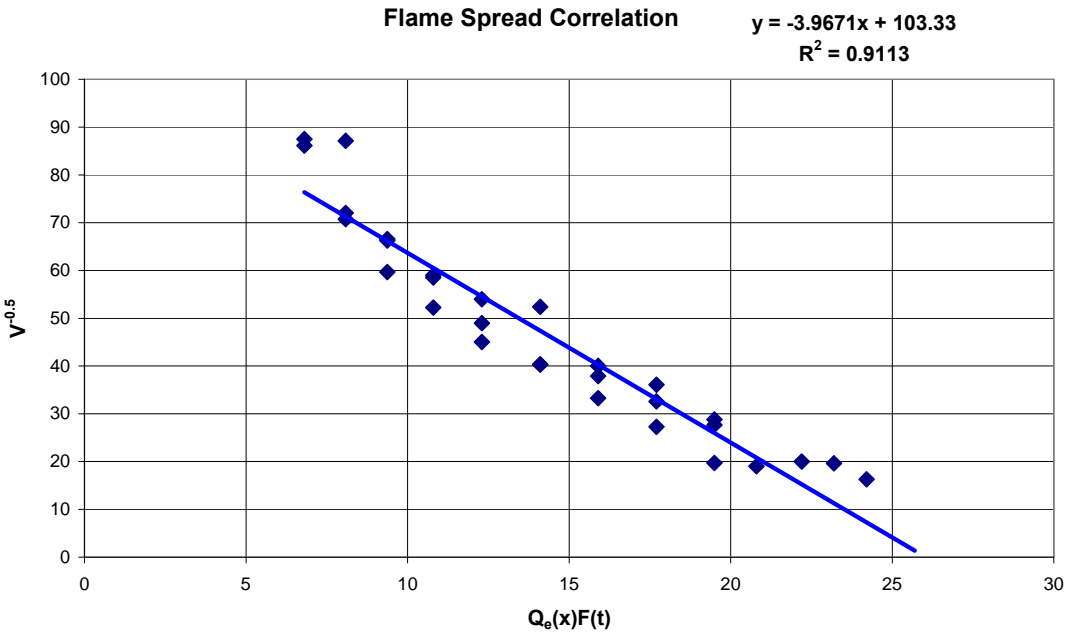


Figure 146: Unscrutinised Flame Spread Correlation for Particle Board

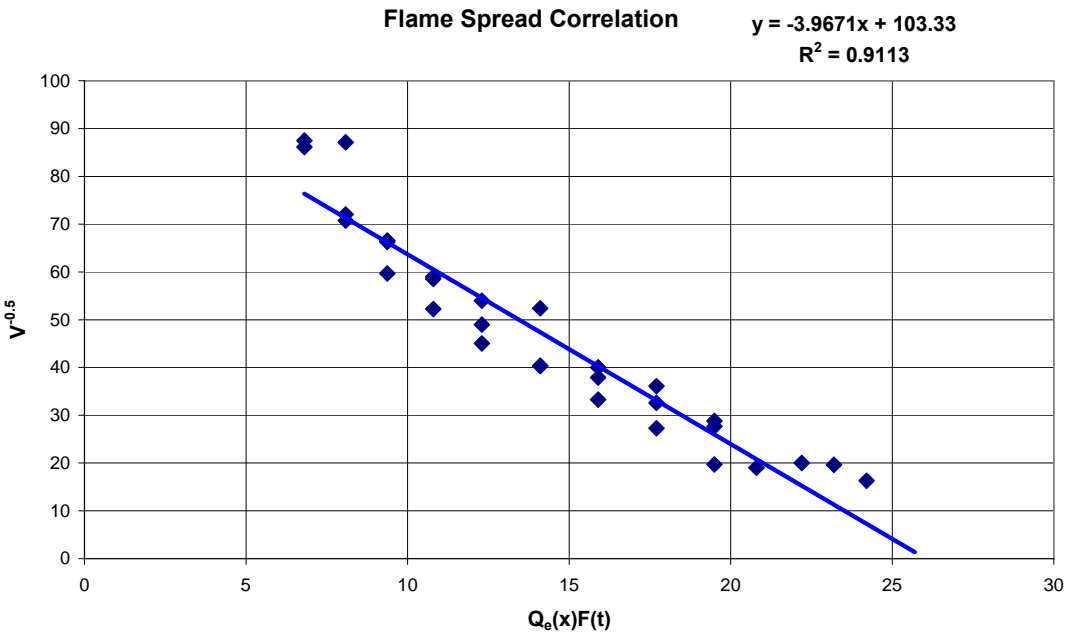


Figure 147: Scrutinised Flame Spread Correlation for Particle Board

The output from the modified ZM method can be seen in Table 72.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0*	10.3	0.911	-
1	11.3	0.912	RIGHT

**Table 72: Particle Board (20mm) Modified Zero-Mean Method Output**

The Particle Board specimen's Mean Residual Error started off at 10.3 % and since this is above the tolerance level of 5 % the ZM methods starts by removing data points from both sides of the correlation. The ZM method tried to remove one cluster of data points from the RHS but this resulted in a Mean Residual Error of 11.3 % which is more than 5 % of the starting residual error, thus the ZM algorithm stopped without removing any data points at all.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE is reasonably close to Merryweather's result shown in Table 73.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$C$ ( $s^{1/2}m^{3/2}kW^{-1}$ )	3.6	3.97

**Table 73: Particle Board (20 mm) ZM Method Output**



10.1.5 Rimu (20 mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s Rimu specimen can be seen in Figure 148, and the plot of scrutinised values can be seen in Figure 149.

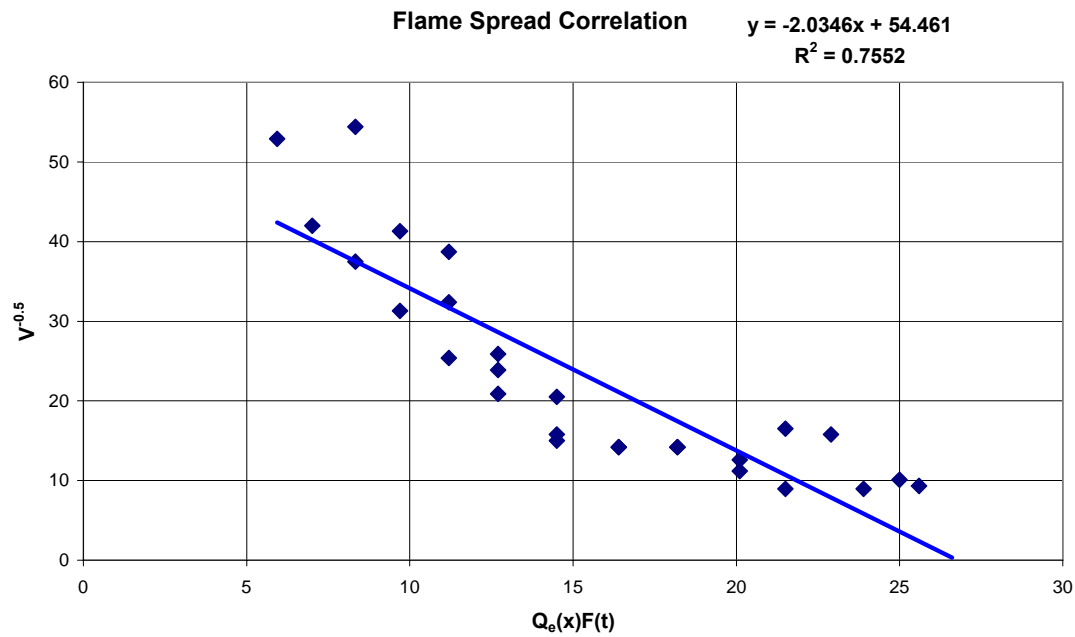


Figure 148: Unscrutinised Flame Spread Correlation for Rimu

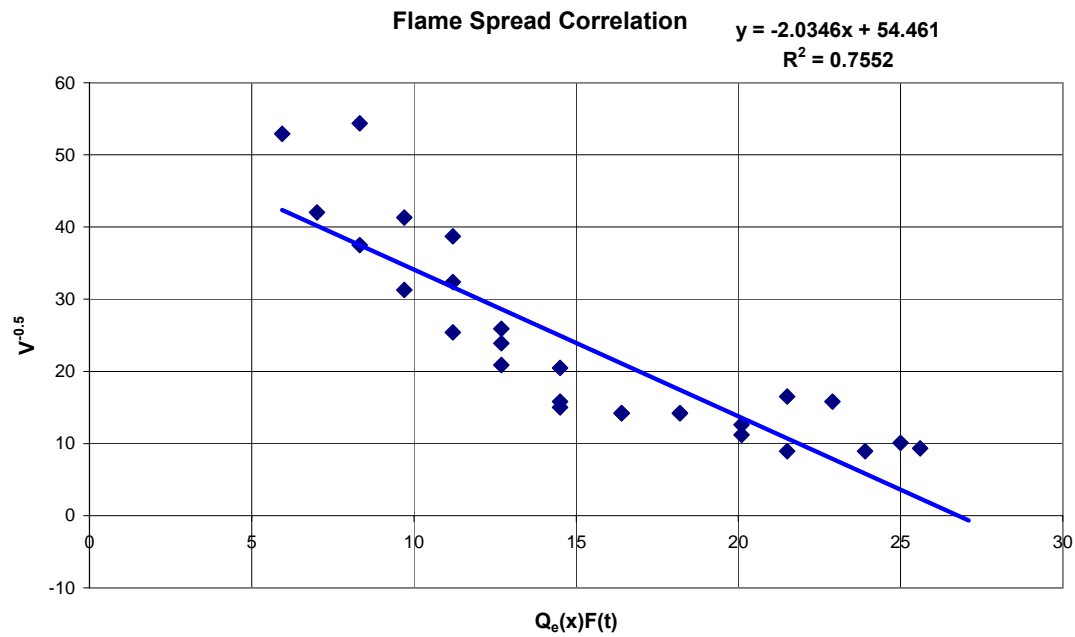


Figure 149: Scrutinised Flame Spread Correlation for Rimu

The output from the modified ZM method can be seen in Table 74.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0*	12.7	0.755	-
1	14.3	0.757	RIGHT

**Table 74: Rimu (20 mm) Modified Zero-Mean Method Output**

The Rimu specimen's Mean Residual Error started off at a value of 12.7 % and since this is above the tolerance level of 5% the ZM method starts by removing data points from both sides of the correlation. The ZM method tried to remove one cluster of data points from the RHS but this resulted in a Mean Residual Error 5% greater than the starting Mean Residual Error, thus the ZM algorithm stopped without removing any data points at all.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does agree with Merryweather's results shown in Table 75.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$C$ ( $s^{1/2}m^{3/2}kW^{-1}$ )	2.2	2.03

**Table 75: Rimu (18 mm) ZM Method Output**

10.1.6 Hardboard (5mm)

The plot of unscrutinised values of the Flame Spread correlation for Merryweather’s Hardboard specimen can be seen in Figure 150, and the plot of scrutinised values can be seen in Figure 151.

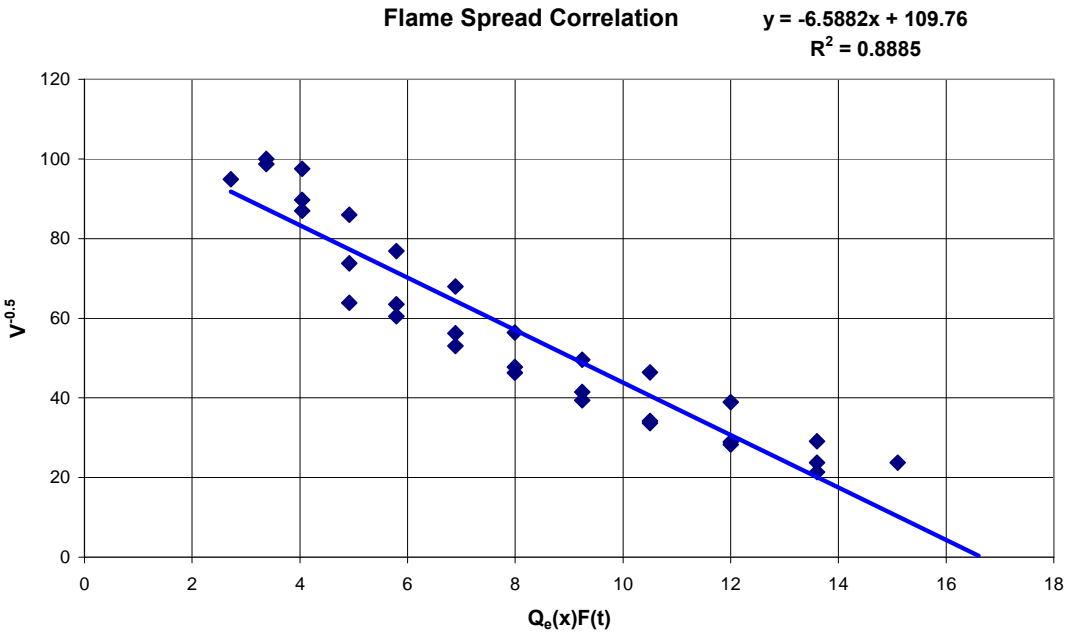


Figure 150: Unscrutinised Flame Spread Correlation for Hardboard

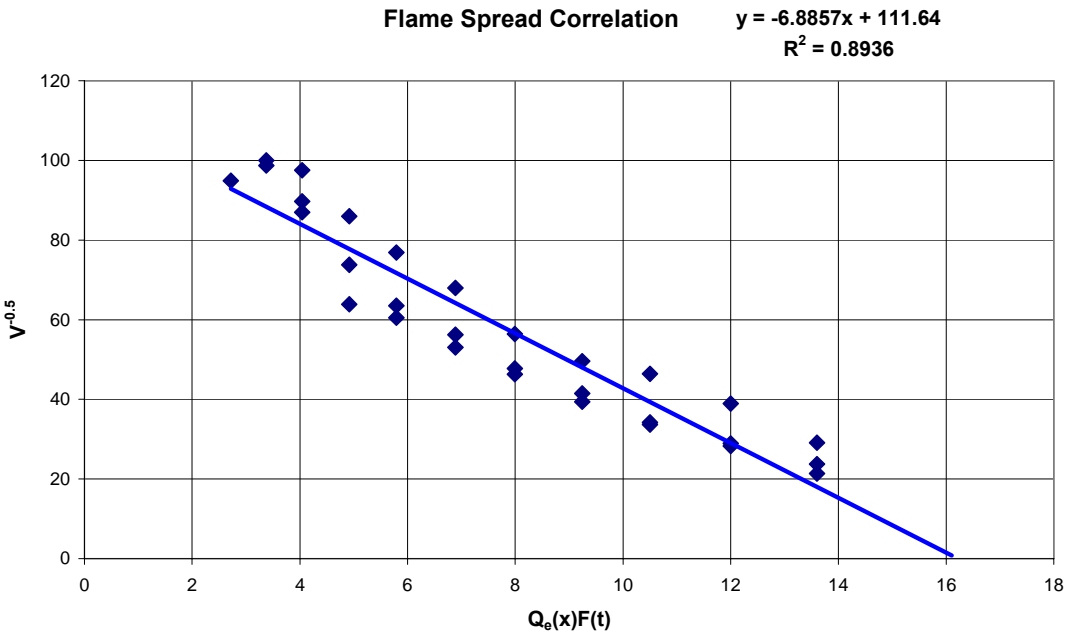


Figure 151: Scrutinised Flame Spread Correlation for Hardboard

The output from the modified ZM method can be seen in Table 76.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0	13.4	0.888	-
1*	3.41	0.894	RIGHT

**Table 76: Hardboard (5mm) Modified Zero-Mean Method Output**

The Hardboard specimen's Mean Residual Error started off at 13.4 % and since this is above the tolerance level of 5 % the ZM starts by removing data points from both sides of the correlation. The ZM removed one cluster of data points from the RHS and then the Mean Residual Error dropped to 3.41 % which is below the threshold value of 5 %.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does not agree with Merryweather's results shown in Table 77.

<b>Parameter</b>	<b>Merryweather [43]</b>	<b>UCFIRE</b>
$C \text{ (s}^{1/2}\text{m}^{3/2}\text{kW}^{-1}\text{)}$	4.9	6.89

**Table 77: Hardboard (5mm) Modified ZM Method Output**

This is a large difference in the  $C$  value when the  $R^2$  value is reasonably high 0.9; the  $C$  is unlikely to change by such a large amount with the removal of one or two more clusters. Perhaps some human error is present here in Merryweather's analysis of the Hardboard specimen.

## **10.2 Babrauskas and Wetterlund's Data**

The ZM method and LIFT data reduction algorithms were then evaluated with some exemplar LIFT ignition test data from Babrauskas and Wetterlund's LIFT [34] experiments. Since the ignition parameters predicted by UCFIRE and Babrauskas and Wetterlund differed significantly for the Insulating Fibreboard, Acrylic Pile Fabric/HR Foam and the Cotton/Kevlar/HR PU Foam specimens these shall be excluded from the analysis of this section.

The experiments were:

- FR PU Foam (40 mm).
- Black PMMA (10 mm).

Babrauskas and Wetterlund made their flame spread measurements in 50 mm increments instead of 25 mm so these had to be linearly interpolated to 25 mm increments; as per *ASTM E 1321-97a*'s requirements.

10.2.1 FR PU Foam (40 mm)

The plot of unscrutinised values of the Flame Spread correlation for Babrauskas and Wetterlund’s FR PU Foam specimen can be seen in Figure 152, and the plot of scrutinised values can be seen in Figure 153.

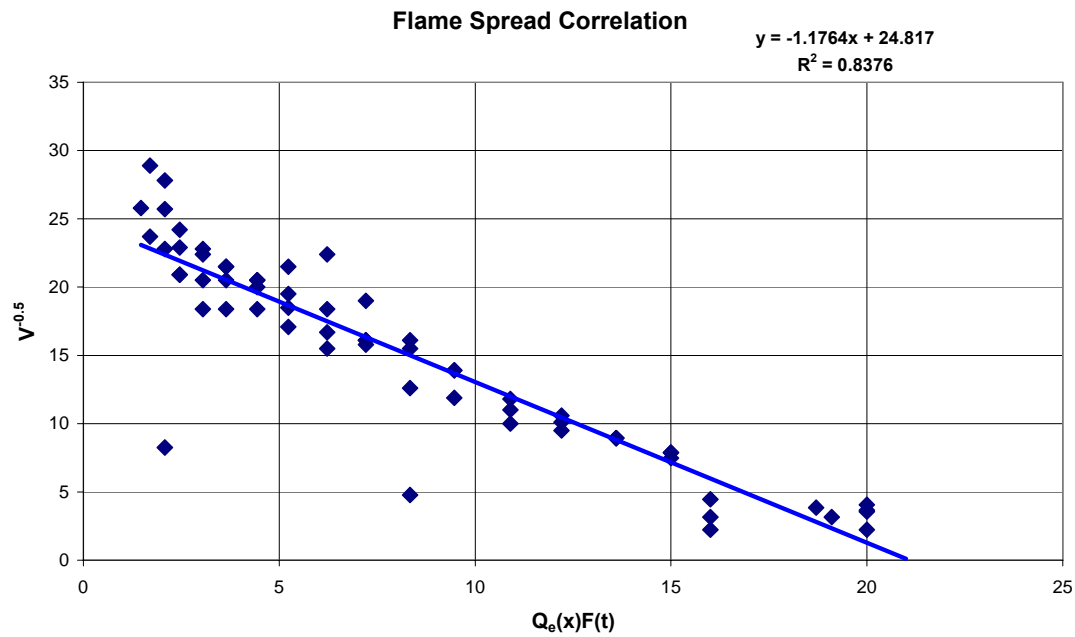


Figure 152: Unscrutinised Flame Spread Correlation for FR PU Foam

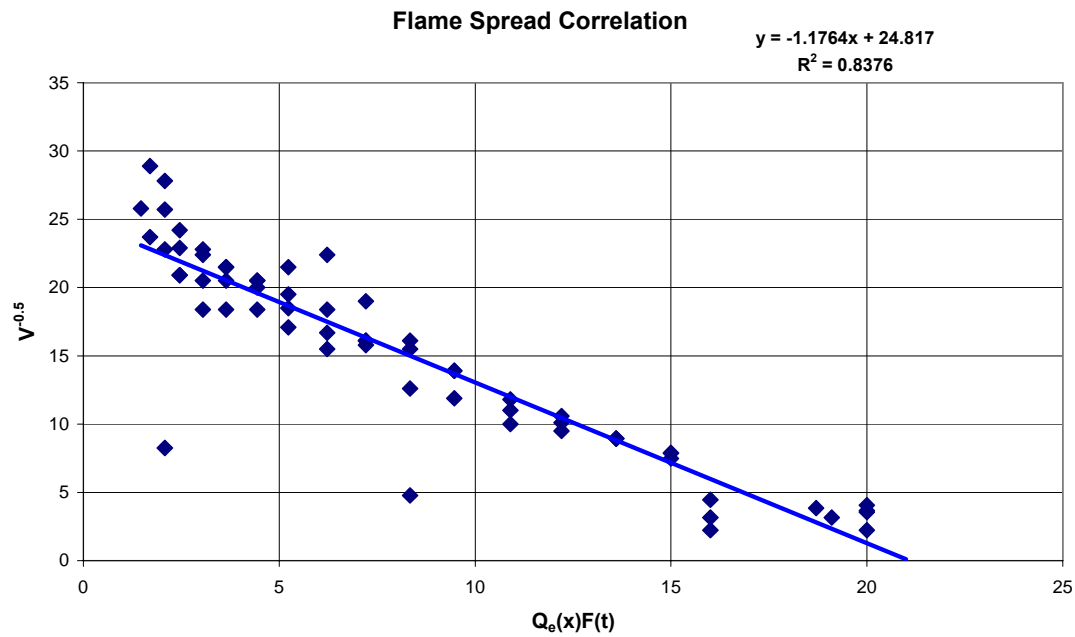


Figure 153: Scrutinised Flame Spread Correlation for FR PU Foam

The output from the Modified ZM method can be seen in Table 78.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0*	8.17	0.838	-
1	7.93	0.834	LEFT

**Table 78: FR PU Foam (40 mm) Modified Zero-Mean Method Output**

FR PU Foam's Mean Residual Error started off at 8.17 % and tries to remove one data cluster from the left hand side of the curve, but this action reduces the  $R^2$  value so it is rejected.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does agree with Babrauskas and Wetterlund's results shown in Table 79.

<b>Parameter</b>	<b>Babrauskas and Wetterlund [34]</b>	<b>UCFIRE</b>
$C \text{ (s}^{1/2}\text{m}^{3/2}\text{kW}^{-1}\text{)}$	1.20	1.17

**Table 79: FR PU Foam (40 mm) ZM Method Output**

10.2.2 Black PMMA (10 mm)

The plot of unscrutinised values of the Flame Spread correlation for Babrauskas and Wetterlund’s Black PMMA specimen can be seen in Figure 154, and the plot of scrutinised values can be seen in Figure 155.

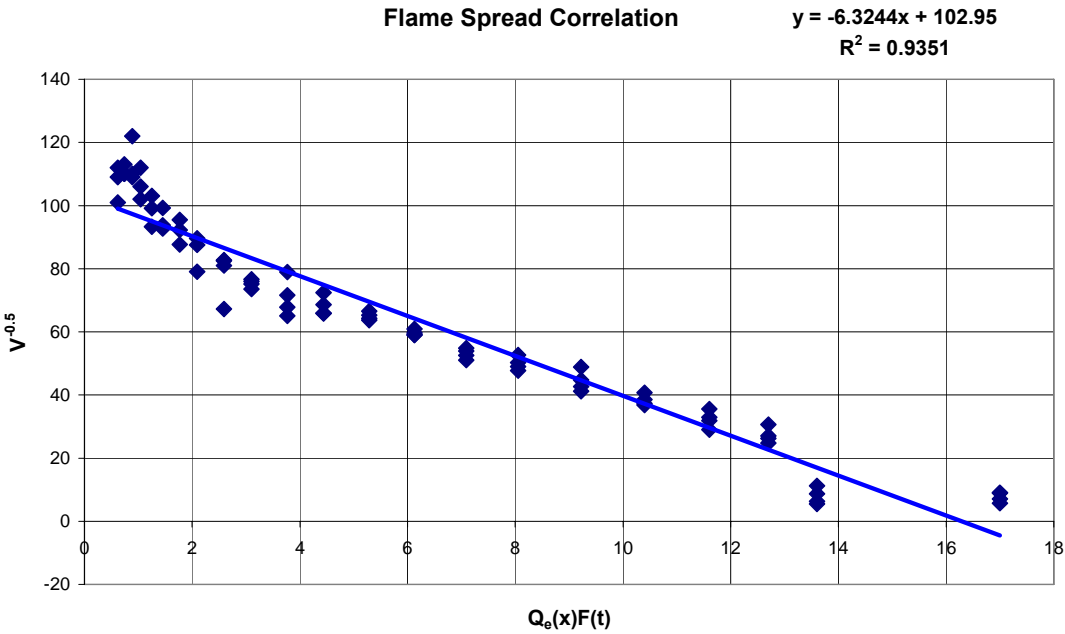


Figure 154: Unscrutinised Flame Spread Correlation for Black PMMA

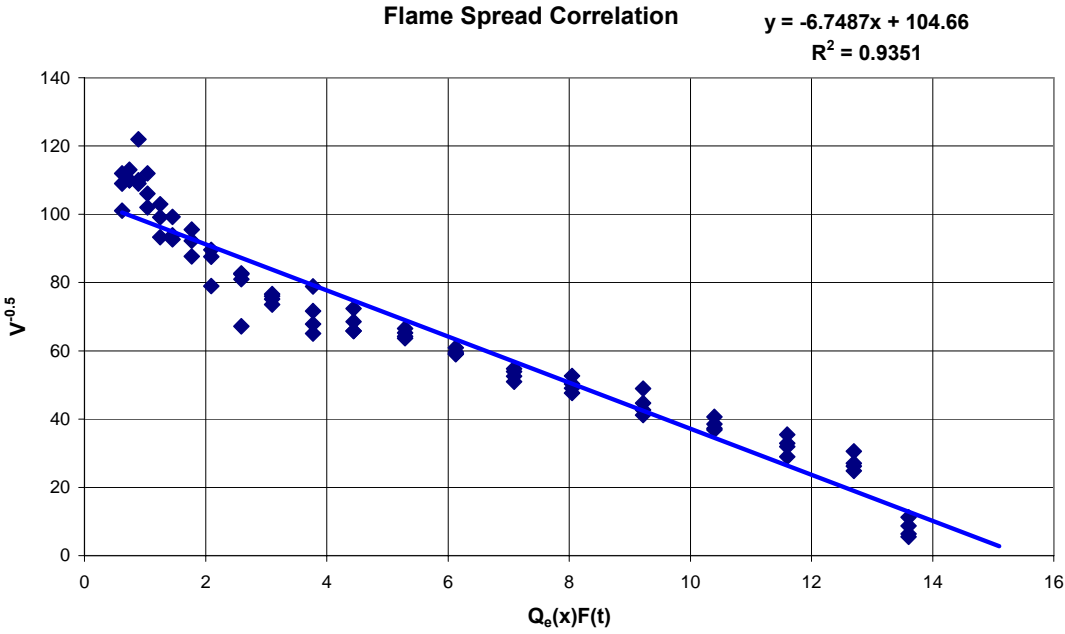


Figure 155: Scrutinised Flame Spread Correlation for Black PMMA



The output from the Modified ZM method can be seen in Table 80.

<b>Iteration</b>	<b>Mean Residual Error (%)</b>	<b><math>R^2</math> Value</b>	<b>Side</b>
0	8.45	0.935	-
1*	6.07	0.935	RIGHT
2	6.38	0.933	LEFT

**Table 80: Black PMMA (10 mm) Modified Zero-Mean Method Output**

The Black PMMA specimen's Mean Residual Error started off at 8.45 % and since this is above the tolerance level of 5 % the ZM method starts by removing data points from both sides of the correlation. The ZM removed one cluster from the RHS, which resulted in a lower Mean Residual Error but no change in  $R^2$  value and then one cluster from the LHS but this action resulted in a higher Mean Residual Error so the algorithm stopped and took the state of the first iteration.

The Flame heat transfer factor ( $C$ ) produced by UCFIRE does agree with Babrauskas and Wetterlund's results shown in Table 81.

<b>Parameter</b>	<b>Babrauskas and Wetterlund [34]</b>	<b>UCFIRE</b>
$C \text{ (s}^{1/2}\text{m}^{3/2}\text{kW}^{-1}\text{)}$	6.99	6.75

**Table 81: Black PMMA (10mm) Modified ZM Method Output**

### **10.3 Summary**

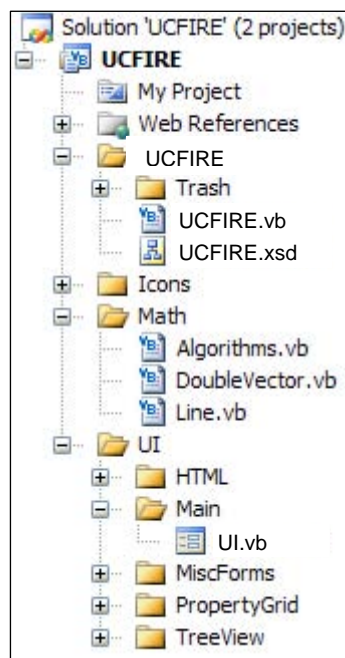
The ZM method and the LIFT data reduction algorithms produce very reasonable results for most of the specimens. However UCFIRE's results for Merryweather's MDF and Hardboard specimens were not reasonably close to the author's value for  $C$ . UCFIRE'S results for a few cases such as Merryweather's Rimu specimen and Babrauskas and Wetterlund's Black PMMA and FR PU Foam specimens almost exactly agrees with the author's value for  $C$ . Perhaps human error is to blame for these discrepancies; particularly in cases such as Merryweather's MDF specimen where the  $R^2$  value is already high and the removal of one or two clusters of points would not sufficiently affect the  $C$  value.

## 11 User and Web Interfaces to UCFIRE Documents

This chapter explores the development of a User Interface (UI) for the UCFIRE DBMS and a web interface to UCFIRE documents stored on a web server.

### 11.1 UCFIRE's User Interface

The UCFIRE algorithm contains all of the routines required to process and reduce raw data from a fire test but the DBMS also needs to be able to interact with the user. Thus it would be necessary to construct a User Interface for the UCFIRE DBMS. The layout of the entire UCFIRE DBMS program can be seen in Figure 156.



**Figure 156: UCFIRE DBMS Layout**

The VB.NET application contains the UCFIRE class and UCFIRE Schema used to process, and reduce the raw fire test data. The Math folder contains classes that support the reduction processes performed by the UCFIRE class and the main UI form. The main UI form of UCFIRE requests information from the user using forms contained within the MiscForms folder. The HTML and PropertyGrid folders are concerned with displaying information within the UCFIRE User Interface. The classes contained within the TreeViews folder controls the TreeViewList objects in the UCFIRE interface. TreeViewList objects will be explained in more detail in the next section.

The aim of this User Interface was to be:

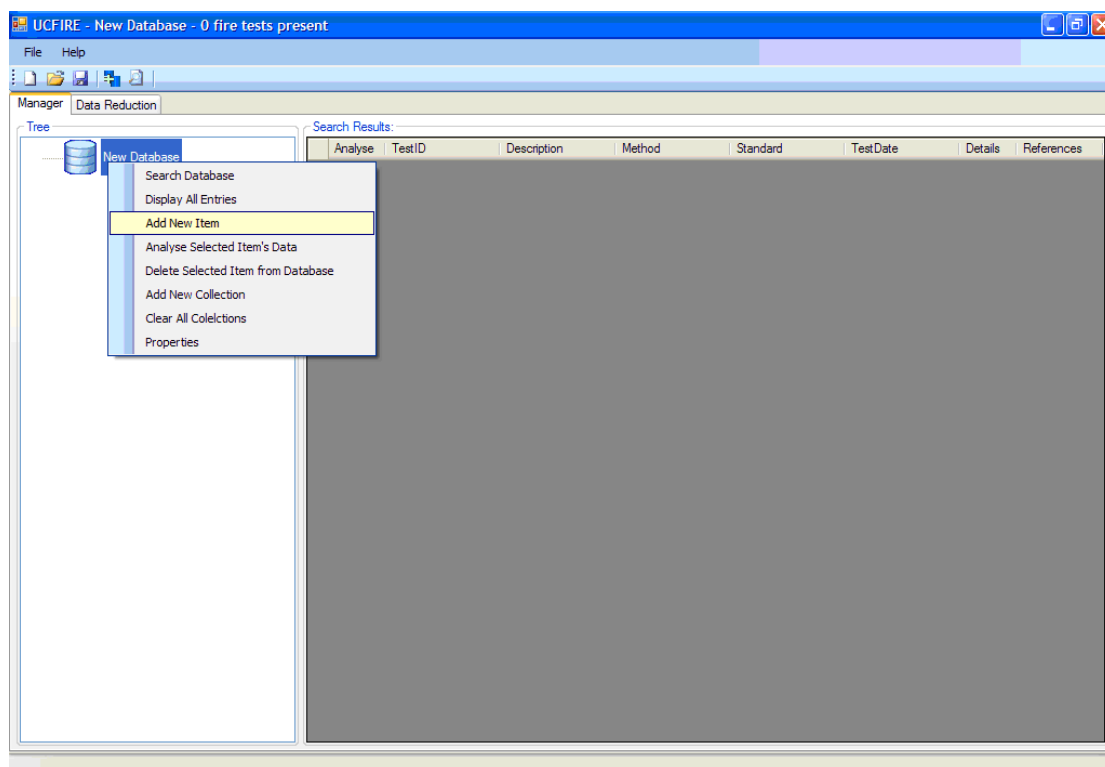
- User friendly.
- Easily extendable.

The UCFIRE interface consists of two main parts:

- The Manager tab.
- The Data Reduction tab.

### 11.1.1 Data Manager Tab

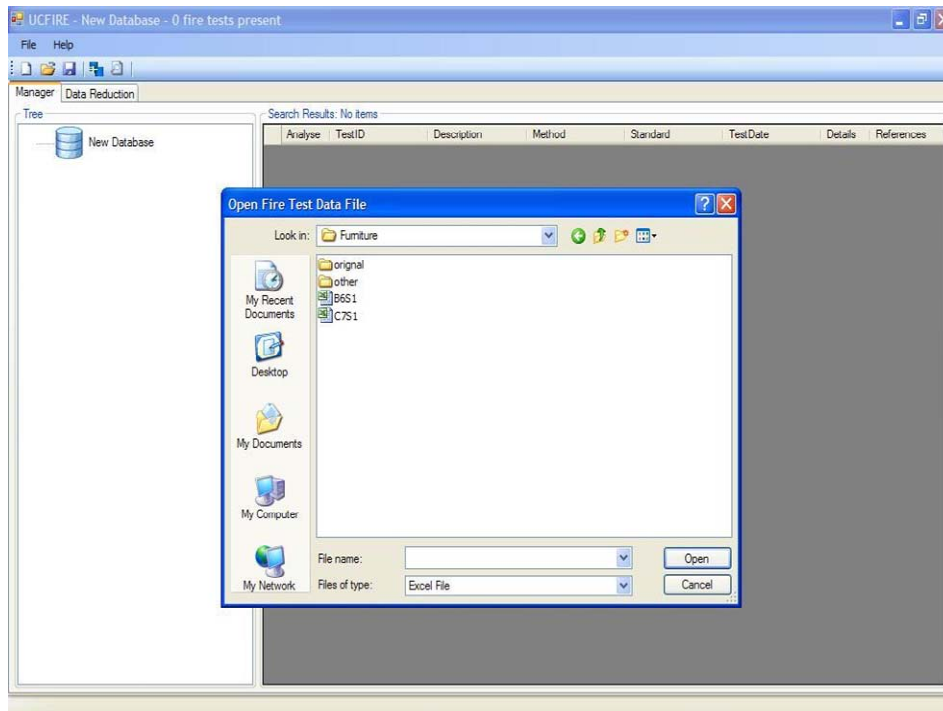
The Data Manager tab is shown in Figure 157.



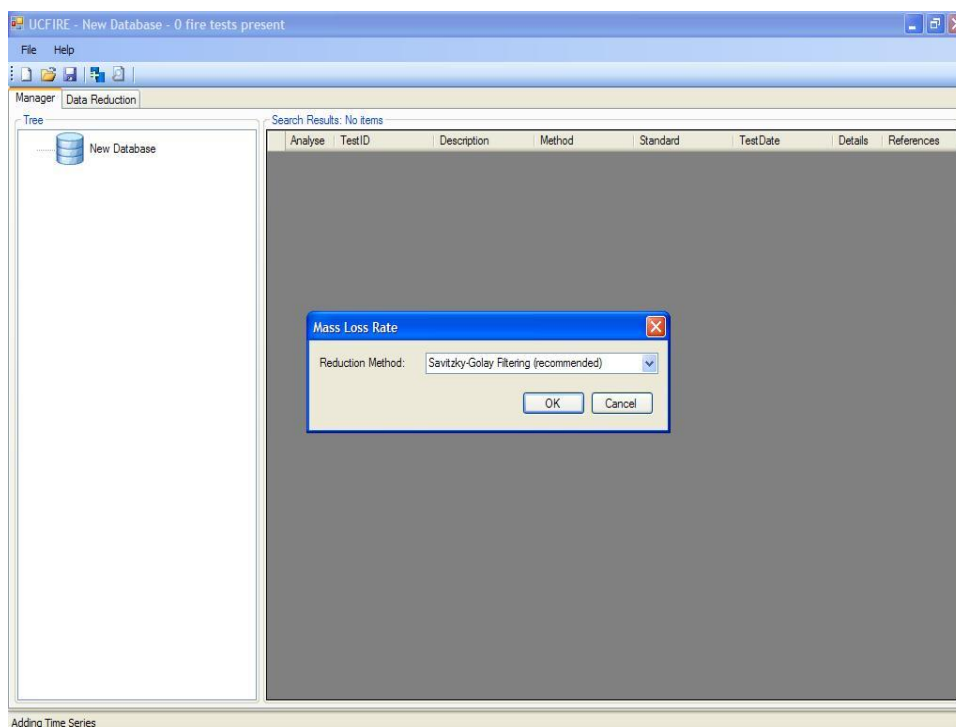
**Figure 157: UCFIRE Interface**

The left portion of the Data Manager tab contains a TreeView List; that is a hierarchical collection of nodes. These nodes may be assigned actions if the user left or right clicks on them. For instance when the user right clicks on the Database node a popup menu is displayed with a number of processing options. Within the manager tab the user may add a new data item, delete data items from the current UCFIRE document or manage lists of database items for group analysis.

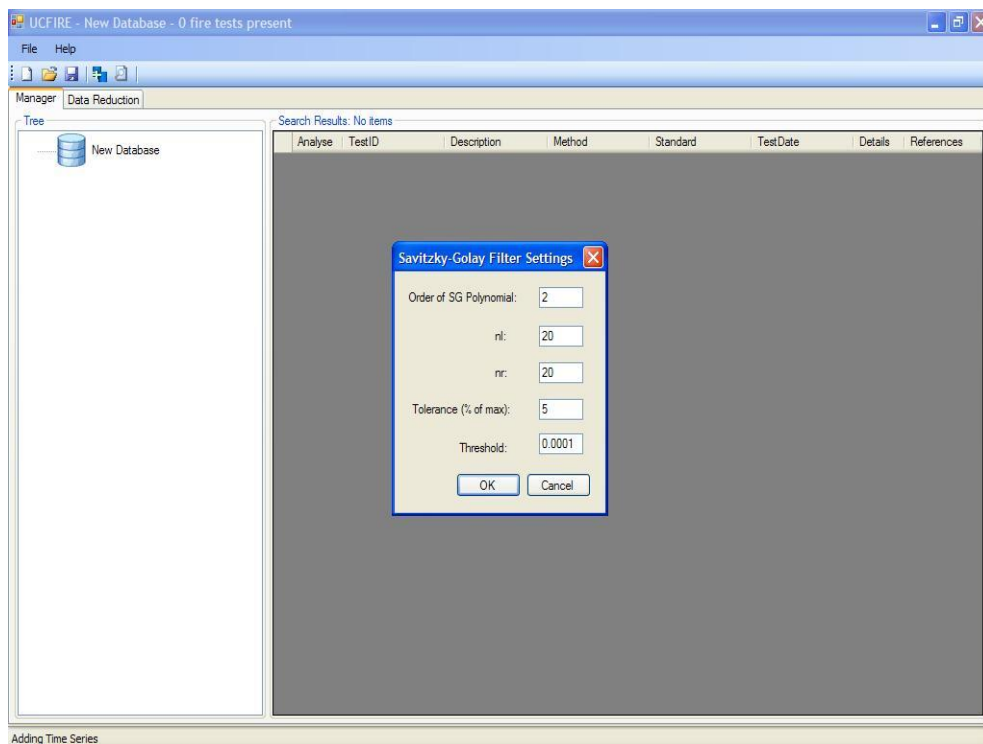
When adding a new fire test to the current UCFIRE DBMS the user is asked to specify the Microsoft Excel spreadsheet containing the fire test as can be seen in Figure 158 and depending on the test some reduction options such as the particular MLR algorithm to be used as shown in Figures 159 and 160.



**Figure 158: Adding a New Fire Test**



**Figure 159: Specifying MLR Reduction Options**



**Figure 160: SVG Settings**

### 11.1.2 Data Reduction Tab

In the Data Reduction tab the user can view the reduced data related to the fire test as shown for an exemplar fire test in Figure 161.

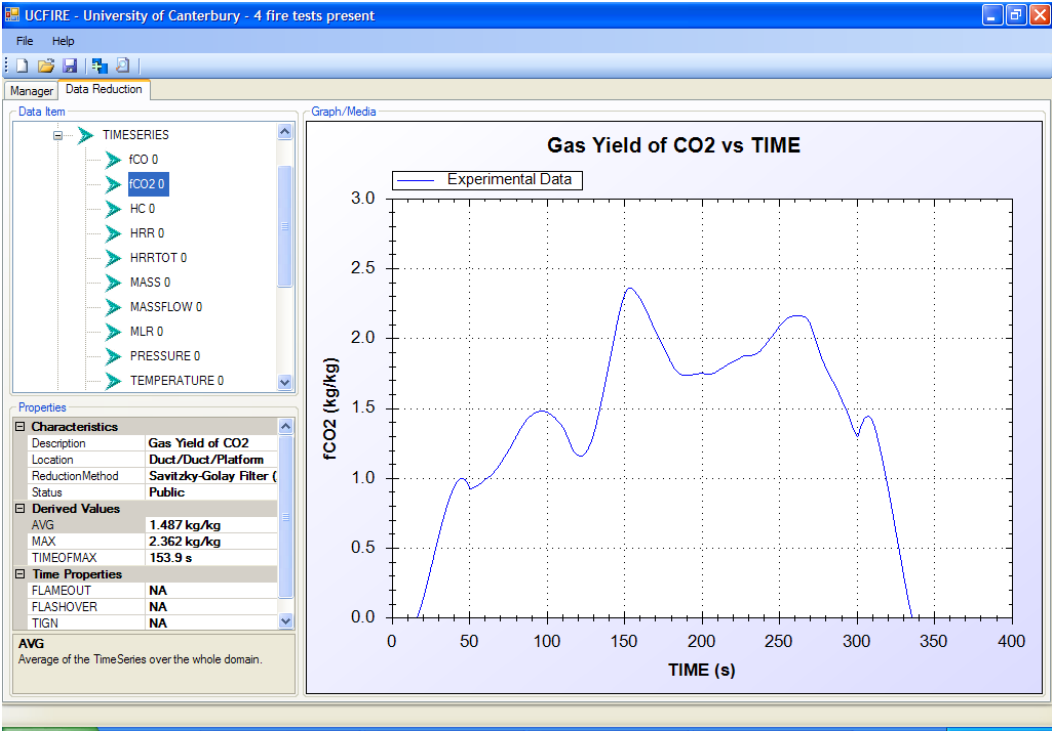
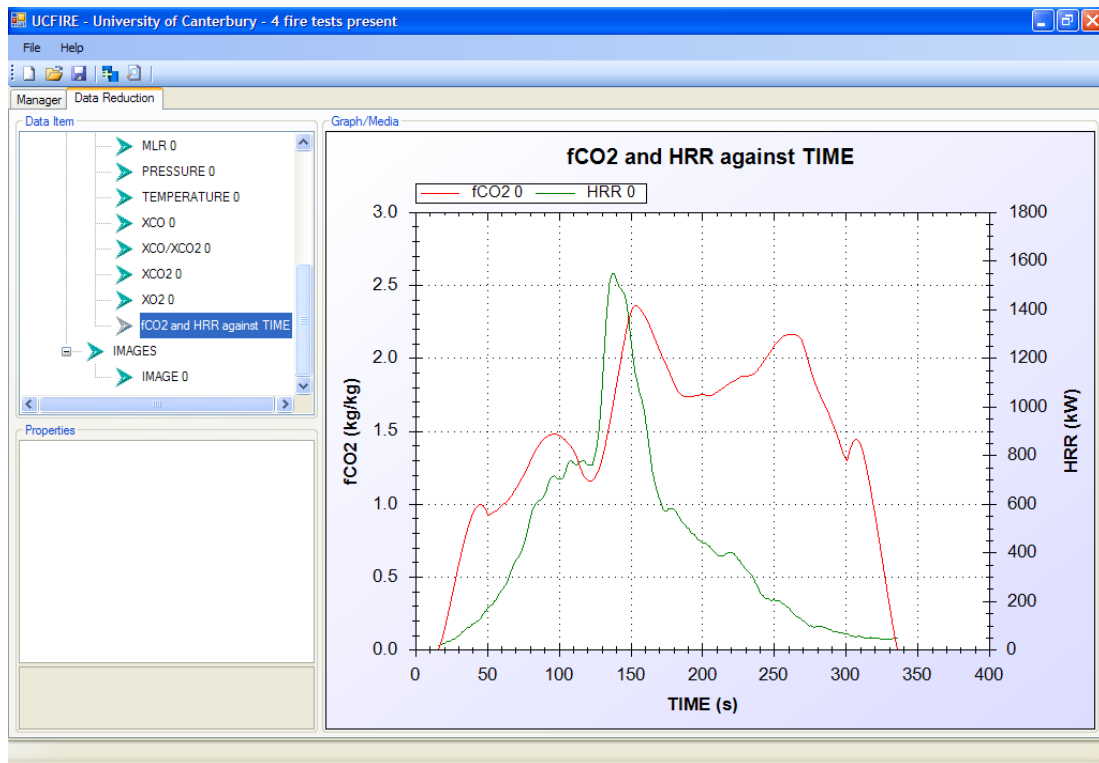


Figure 161: Data Reduction Tab of UCFIRE

The most interesting feature of the User Interface is that the user can compare multiple time series within the UCFIRE as can be seen in Figure 162.



**Figure 162: Comparing Multiple Time-Series within UCFIRE**

The user can also filter time series using the SVG algorithm or an n-point moving average within the UCFIRE interface.



### 11.1.3 Multiple Time Series Analysis

The UCFIRE interface is easily extendable and provides facilities for future researchers to build on, such as the ability to create groups of fire tests and perform joint analysis on them. An example of this can be seen in Figure 163 where a collection of fire tests were formed in the Data Manager and the option to calculate the 0.95 curves for the time series stored in each fire tests is presented in a popup menu. While not implemented in this thesis a function could be developed to predict a reasonable worst case fire curve for a group of related fire tests.

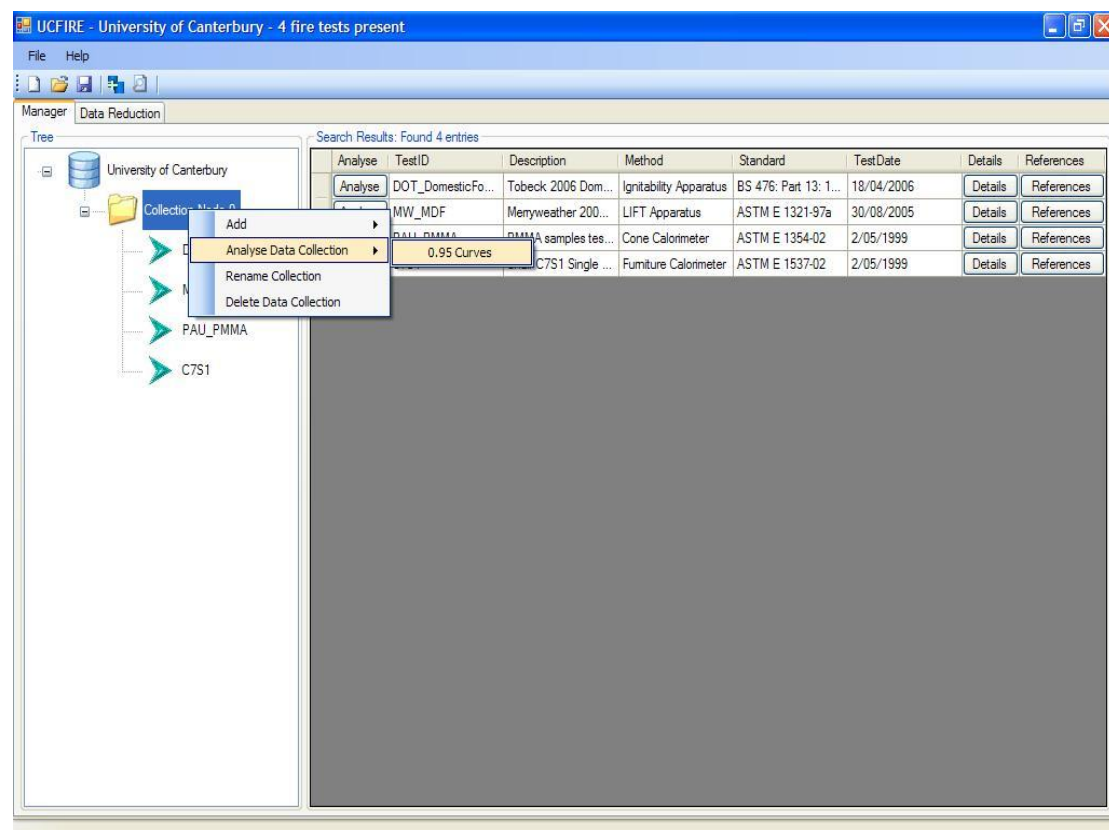


Figure 163: Joint Analysis of Fire Tests

## **11.2 Integrating UCFIRE with the Web**

This section of the thesis explains the motivation behind integrating UCFIRE with the internet and how this was achieved.

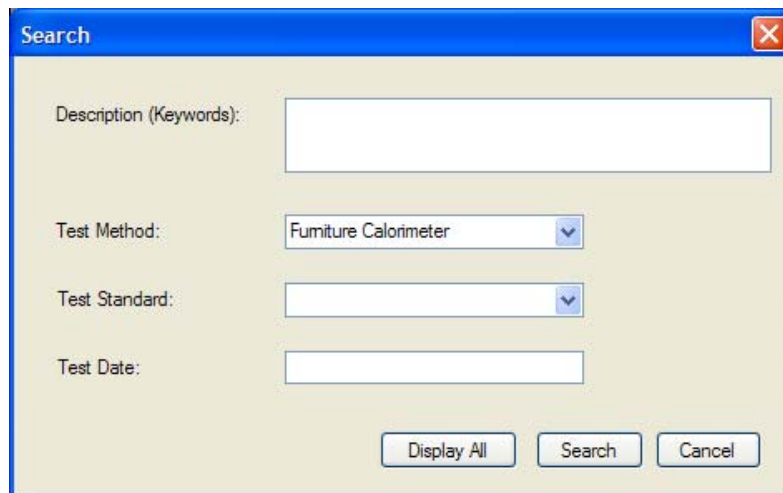
The file size for one of the sofa fire test performed by Hill [31] consumes roughly 0.2 Megabytes of space without images or video clips. The data size requirements for a database containing 1,000 fire tests would be of the order of 200 Megabytes for just the XML data. However this requirement is dwarfed by the file size of Hill's accompanying video clip of 230 Megabytes for just one fire test.

Currently all the XML data for a local UCFIRE document is loaded directly into memory but performing this process for a UCFIRE document located on a web server would be extremely inefficient and costly; particularly if the user only wished to browse the fire tests present within the UCFIRE document.

To overcome this limitation it was decided to build an ASP.NET Web Service which will intercept a UCFIRE client's request and filter out the unnecessary information and deliver only the required fire test data to the UCFIRE client.

### **11.2.1 The WEBFIRE Web Service**

The ASP.NET Web Service (WEBFIRE) was created in the Visual Studios Integrated Design Environment (IDE). Instead of UCFIRE loading the entire XML file into memory the user is prompted to search for a specific fire test as seen in Figure 164, or to display the heading information for all of the fire tests stored within the UCFIRE DBMS



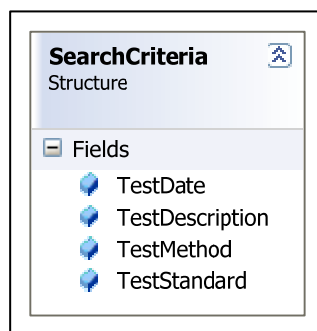
The image shows a 'Search' dialog box with a blue title bar and a close button. It contains four input fields: 'Description (Keywords):' (a text box), 'Test Method:' (a dropdown menu with 'Furniture Calorimeter' selected), 'Test Standard:' (a dropdown menu), and 'Test Date:' (a text box). At the bottom, there are three buttons: 'Display All', 'Search', and 'Cancel'.

**Figure 164: Search Dialog Box**

The user is allowed to search using 4 different criteria:

- Keywords contained within the Test Description.
- The Test Method e.g. Furniture calorimeter.
- The Test Standard e.g. *ASTM E 1321-97a*.
- The Test Date which must be exactly the same as the test item's test date before the data item is included in the search results.

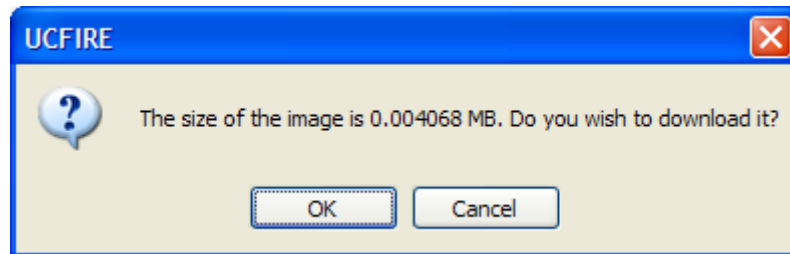
The search criteria structure that is passed from the UCFIRE client to WEBFIRE can be seen in Figure 165.



**Figure 165: Search Criteria**

Note that at this stage only the heading information for each data item is passed to the UCFIRE client to save bandwidth, the full XML for each data item is only downloaded (with the *GetDataItem* web method) if the user clicks on the analyze, details or references buttons of the data grid control in the manager tab of UCFIRE.

Images and video clips for a particular data item are not automatically downloaded with the complete XML data; the user is first informed as to the size of the file (Figure 166) and then asked if they would like to download it.



**Figure 166: Download Media Dialog Box**

Since Web Services transmit information using XML the image or video clip must be converted into a binary stream of data at the server end (WEBFIRE) and then reconstructed at client end (UCFIRE). This method will need to be modified later to allow for the downloading of large media files as control messages must be embedded into the binary data stream to keep the web connection alive.

At any time the UCFIRE document may be updated on the web server; so each time the UCFIRE DBMS requests information from a UCFIRE document stored on a web server the last modified time element in the UCFIRE document is compared with the time recorded when the UCFIRE DBMS first connected to WEBFIRE. If there is a discrepancy the user is warned and the UCFIRE client is restarted with the search dialog box (Figure 164) visible.

## **12 Conclusions and Recommendations**

### ***12.1 Conclusions***

The most extensible and complete fire test database (UCFIRE) available in the fire engineering community was created and this allowed test data to be collected, reduced and stored away in a logical and complete fashion.

UCFIRE can store the following test types: Cone Calorimeter, Furniture Calorimeter, Room/Corner Test, LIFT and Ignitability Apparatus Tests. The UCFIRE DBMS was designed to be extensible and with minor effort additional fire tests can be added to this list.

UCFIRE overcame one prominent limitation of existing DBMS in that they do not allow for the semi-automated reduction of fire test data; making the data reduction process error prone and time consuming. It is possible for UCFIRE to reduce a fire test and store the data in a matter of seconds as opposed to the time consuming process that would be necessary for a human to perform.

The goal of the UCFIRE DBMS to allow open access to its high quality fire test data in the most efficient and useful manner was fulfilled by the development of an ASP.NET Web Service that prevented the entire UCFIRE DBMS being downloaded at the first instance by filtering out unnecessary fire tests and delivering only the desired data. This web service is currently in service on the University of Canterbury's Civil Engineering web server.

A number of time series reduction algorithms were developed and tested on exemplar data; these were then incorporated into the UCFIRE DBMS. The most complex of these algorithms allowed the Mass Loss Rate to be calculated reliably and autonomously.

An unbiased and mechanistic algorithm was developed based on the assumptions underlining the theory of linear regression and this algorithm was used to scrutinise exemplar LIFT ignition test data. The ZM algorithm is generally similar to the human approach but there are some differences due to human error and the non-application of the data reduction technique.

The ZM method was modified and applied to the LIFT Critical Flux correlation but this correlation seemed less susceptible to deviations brought on by the loss of heat energy near the critical flux than the Thermal Response correlation.

The ZM method was modified and applied to the LIFT Flame Spread correlation. The ZM method and the LIFT data reduction algorithms produced equivalent results for most of the fire tests; although a few discrepancies were present that may be the result of human error.

## **12.2 Recommendations**

It is recommended that the file format of the UCFIRE DBMS be improved by merging the UCFIRE XML document with the folders containing the media files into one single compressed folder. However this cannot be done until the file size limit of Microsoft's compression algorithms is increased above 4 Gigabytes.

It is recommended that control messages be embedded into the binary stream of data used to transmit images and video files between a UCFIRE document stored on a web server and the UCFIRE interface; to keep the web connection alive and to allow for the transmission of larger media files. At present the web connection is often automatically shut down before a large media file can be transferred.

It is recommended that the *ASTM 1354-02* MLR algorithm should be replaced with the modified SVG algorithm presented in this thesis. It is also recommended that this algorithm should also be adopted in the Furniture Calorimeter standard, *NT FIRE 032*.

There is potential for a future student/researcher to expand on UCFIRE/WEBFIRE and start analyzing collections of data items. For instance it is possible to group related fire tests into collections within the data manager of the UCFIRE interface. Once the test items have been entered into a collection it would then be possible to determine 0.95 HRR curves for the collection and perform other types of analysis to the collection of fire tests. Due to time constraints this was not pursued but would be an interesting and important research topic for another person to pick up from.

The Zero-Mean algorithm for the Thermal Response Correlation should be tested on a larger dataset of LIFT ignition data to further prove the efficacy of the algorithm.

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## Appendix A: FDMS 2.0 Derived Measurements

ID	Name	Description	Units
0	AREA	Specimen Area	m <sup>2</sup>
1	ASCARITE	Indicates if CO <sub>2</sub> was removed from the sample before O <sub>2</sub> was measured using Ascarite or equivalent means.	
2	AVGCO	Test average of the CO yield	kg/kg
3	AVGCO <sub>2</sub>	Test average of the CO <sub>2</sub> yield	kg/kg
4	AVGH <sub>2</sub> O	Test average of the H <sub>2</sub> O yield	kg/kg
5	AVGHC	Test average of the effective heat of combustion	MJ/kg
6	AVGMDOT	Test average of the mass loss rate	kg/s
7	AVGQDOT	Test average of the rate of heat release	kW
8	AVGSIGMA	Test average of the specific smoke extinction area	m <sup>2</sup> /kg
9	B-LIFT	LIFT ignition parameter	s <sup>-1/2</sup>
10	BURNER	Burner heat release rate	kW
11	BURNSPEC	Heat output values specified for the burner program	
12	C-CONE	Orifice constant as determined from the CH <sub>4</sub> burner calibration	
13	C-LIFT	Slope of the correlated flame spread data	s <sup>1/2</sup> m <sup>1/2</sup> W <sup>-1</sup>
14	CO60	Average CO yield over 60s subsequent to ignition	kg/kg
15	CO180	Average CO yield over 180s subsequent to ignition	kg/kg
16	CO300	Average CO yield over 200s subsequent to ignition	kg/kg

ID	Name	Description	Units
17	CONDUCT	Conductivity	Energy absorption rate * length <sup>-1</sup>
18	COPROD	Production rate of Carbon Monoxide	g/s
19	COSTACK	Carbon monoxide concentration in the exhaust stack	
20	COYIELD	Carbon monoxide yield	kg/kg
21	CO260	Average CO2 yield over 60s subsequent to ignition	kg/kg
22	CO2180	Average CO2 yield over 180s subsequent to ignition	kg/kg
23	CO2300	Average CO2 yield over 200s subsequent to ignition	kg/kg
24	CO2PROD	Production rate of Carbon Dioxide	g/s
25	CO2STACK	Carbon Dioxide concentration in the exhaust stack	
26	CO2YIELD	Carbon Dioxide yield	kg/kg
27	DENSITY	Density	kg/m <sup>3</sup>
28	E	Oxygen consumption constant	kJ/g
29	EXTCOEFF	Smoke extinction coefficient in exhaust stack	m <sup>-1</sup>
30	FLAMEOUT	Time to flameout	s
31	FLASH	Time when flashover occurs in the room	s
32	FLOW	Flow rate of the burner	kg/s
33	FLOWDUCT	Duct flow rate	kg/s
34	FLOWGAS	Flow rate of gas to ignition burner	kg/s
35	FLOWVEL	Volumetric flow rate	m <sup>3</sup> /s
36	FLUX	Flux	kW/m <sup>2</sup>
37	FLUXCEIL	Heat flux measurement at compartment ceiling	kW/m <sup>2</sup>

ID	Name	Description	Units
38	FLUXFLOR	Heat flux measurement at compartment floor	kW/m <sup>2</sup>
39	FRAME	Denotes if the edge flame was used	-
40	GRID	Denotes if the wire grid was used	-
41	H2O60	Average H2O yield over 60s subsequent to ignition	kg/kg
42	H2O180	Average H2O yield over 180s subsequent to ignition	kg/kg
43	H2O300	Average H2O yield over 200s subsequent to ignition	kg/kg
44	H2OPROD	Production rate of water vapour	g/s
45	H2OSTACK	Water vapour concentration in the exhaust stack	-
46	H2OYIELD	Water vapour yield	kg/kg
47	HBR	HBR yield	kg/kg
48	HC	Effective heat of combustion	MJ/kg
49	HC60	Average heat of combustion over 60s subsequent to ignition	MJ/kg
50	HC180	Average heat of combustion over 180s subsequent to ignition	MJ/kg
51	HC300	Average heat of combustion over 200s subsequent to ignition	MJ/kg
52	HCL	HCL yield	kg/kg
53	HCLPROD	Production rate of HCL	g/s
54	HCLSTACK	HCL concentration in the exhaust stack	
55	HCLYIELD	HCL yield	kg/kg
56	HCN	HCN yield	kg/kg
57	HRR	Heat release rate	kW
58	HRR/A	Heat release rate per unit area	kJ/m <sup>2</sup>
59	HRRTOT	Total heat released	kJ
60	IGNITOR	Ignition type used	-

ID	Name	Description	Units
61	IGNTYPE	Ignition type	-
62	INERTIA	Thermal inertia	$\text{kW}^2\text{sm}^{-4}\text{K}^{-2}$
63	IRRAD	Heat flux calibration meter	$\text{kW/m}^2$
64	LOCATION	Location of the specimen	-
65	MASS	Specimen mass	kg
66	MASS/A	Specimen mass per unit area	$\text{kg/m}^2$
67	MASSF	Specimen mass at the end of the test	kg
68	MASSFLOW	Mass flow rate	kg/s
69	MASSI	Specimen mass before the start of the test	kg
70	MASSLOSS	Specimen mass loss during the test	kg
71	MAXEXT	Maximum value of the smoke extinction area flow rate	$\text{m}^2/\text{s}$
72	MAXMDOT	Peak mass loss rate	$\text{g}/(\text{sm}^2)$
73	MAXQDOT	Peak rate of heat release	kW
74	MAXSIGMA	Peak specific smoke extinction area	$\text{m}^2/\text{kg}$
75	MAXTIME	Time to peak heat release	s
76	MDOT60	Average mass loss rate over 60s since ignition	$\text{g}/(\text{sm}^2)$
77	MDOT180	Average mass loss rate over 180s since ignition	$\text{g}/(\text{sm}^2)$
78	MDOT300	Average mass loss rate over 300s since ignition	$\text{g}/(\text{sm}^2)$
79	MLR	Mass loss rate of the sample	g/s
80	MLR/A	Mass loss rate of the sample per unit area	$\text{g}/(\text{sm}^2)$
81	MOUNT	Specific means of mounting	-
82	O2SUPPLY	Oxygen concentration in the supply air	-
83	O2STACK	Oxygen concentration in the exhaust stack	-
84	ORIENT	Specimen orientation horizontal or vertical	-
85	OXYGEN	Nominal value of oxygen concentration in the enclosure around the heater and sample	-
86	PHI	Flame heating parameter	$\text{kW}^2/\text{m}^3$

ID	Name	Description	Units
87	PILOT	Indicates if ignition was piloted	-
88	PRESORI	Pressure drop across the exhaust orifice plate	Pa
89	PRESORB	Pressure drop across bi-directional flow probe	Pa
90	PRESTUBE	Pressure difference at pilot-static tube	Pa
91	PYRLYSIS	Pyrolysis rate	-
92	QDOT60	Average rate of heat release over 60s since ignition	kW
93	QDO180	Average rate of heat release over 1800s since ignition	kW
94	QDOT300	Average rate of heat release over 300s since ignition	kW
95	QIG	Minimum flux for ignition	kW/m <sup>2</sup>
96	QSMIN	Minimum flux for spread	kW/m <sup>2</sup>
97	RHCOND	Relative humidity for specimen conditioning	%
98	RHTEST	Relative humidity of the supply air for conducting the test	%
99	SEA	Smoke specific extinction area in the exhaust stack	m <sup>2</sup> /s
100	SEARATE	Smoke extinction area flow rate	m <sup>2</sup> /s
101	SIGMA60	Average specific smoke extinction area over 60s since ignition	m <sup>3</sup> /kg
102	SIGMA180	Average specific smoke extinction area over 180s since ignition	m <sup>3</sup> /kg
103	SIGMA300	Average specific smoke extinction area over 300s since ignition	m <sup>3</sup> /kg
104	SOOT	Ratio of the mass of soot deposited on the soot filter to the mass of the specimen loss during the test	-

<b>ID</b>	<b>Name</b>	<b>Description</b>	<b>Units</b>
105	SOOTMASS	Soot mass sampler flow rate	kg/s
106	SPHEAT	Specific heat	MJ/kg/°C
107	SUMEXT	Total smoke extinction area released during the test	m <sup>2</sup>
108	SURFDENS	When thin textiles, papers etc are covering some standard substrate, it is most appropriate to describe them by their surface density	kg/m <sup>3</sup>
109	TEMP1	Temperature at specimen location 1	°C
110	TEMP2	Temperature at specimen location 2	°C
111	TEMP3	Temperature at specimen location 3	°C
112	TEMPCOND	Temperature for specimen conditioning	°C
113	TEMPFLOW	Temperature at the flow measuring station	°C
114	TEMPGAS	Temperature of the gas at a specific depth in the compartment	°C
115	TEMPLAS	Temperature at laser extinction beam	°C
116	TEMPORI	Temperature at the orifice plate	°C
117	TEMPSMK	Temperature at the smoke meter	°C
118	TEMPSTCK	Temperature of gas in exhaust stack	°C
119	TEMPSURF	Surface temperature of the ceiling or wall a specified location	°C
120	TEMPTEST	Temperature of the supply air for conditioning the test	°C
121	THICK	Specimen thickness	m
122	TIG	Minimum temperature for ignition	°C
123	TIGN	Time to ignition	S
124	TIME	Time from start of the ignition source	S
125	TOTLHEAT	Total heat released during the test	MJ
126	TOTLHEAT/A	Total heat released during the test per unit area	MJ/m <sup>2</sup>
127	TSMIN	Minimum temperature for spread	°C



<b>ID</b>	<b>Name</b>	<b>Description</b>	<b>Units</b>
128	TSTAR	Characteristic equilibrium or thermal steady state time	s
129	TUH	Total unburned fuel	kg/kg
130	TUHSTACK	Total unburned hydrocarbon concentration in the exhaust stack	-
131	TUHYIELD	Total unburned hydrocarbons yield	kg/kg
132	VELOCITY	Velocity	m/s
133	VOLLAS	Volumetric flow rate	m <sup>3</sup> /s
134	VOLSTACK	Volumetric flow rate in the exhaust stack	m <sup>3</sup> /s
135	VOLUME	Volume	m <sup>3</sup>

## Appendix B: UCFIRE Schema

```
<?xml version="1.0" encoding="UTF-8"?>

<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">

  <!-- UCFIRE Document - Root Element !-->
  <xs:element name="UCFIRE">
    <xs:complexType>
      <xs:sequence>
        <xs:element name="Version" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
        <xs:element name="Created" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
        <xs:element name="LastModified" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
        <xs:element name="Author" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
        <xs:element name="Description" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
        <xs:element ref="Items" minOccurs="1" maxOccurs="1"/></xs:element>
      </xs:sequence>
    </xs:complexType>
  </xs:element>

  <!-- The items element must contains 1 or more fire tests/exeriments -->
  <xs:element name="Items">
    <xs:complexType>
      <xs:sequence>
        <xs:element ref="Item" minOccurs="1" maxOccurs="unbounded"/></xs:element>
      </xs:sequence>
    </xs:complexType>
  </xs:element>

  <!-- The fire test/experiment item element -->
  <xs:element name="Item">
    <xs:complexType>
      <xs:sequence>
```

```

    <xs:element name="TestID" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
    <xs:element ref="Summary" minOccurs="1" maxOccurs="1"></xs:element>
    <xs:element ref="Details" minOccurs="1" maxOccurs="1"></xs:element>
    <xs:element ref="References" minOccurs="1" maxOccurs="1"></xs:element>
    <xs:element ref="Data" minOccurs="1" maxOccurs="1"></xs:element>
  </xs:sequence>
</xs:complexType>
</xs:element>

<!-- The summary element -->
<xs:element name="Summary">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Description" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element ref="Method" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element ref="Standard" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestDate" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<!-- This element contains details about the type of test performed and who performed it -->
<xs:element name="Details">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="Description" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestSeriesID" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestNumber" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="NumberOfTests" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestOperator" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestOrganisation" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="OrganisationsAddress" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestSponsor" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="SponsorsAddress" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="TestRequester" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="RequestersAddress" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

        </xs:sequence>
    </xs:complexType>
</xs:element>

<!-- The test method element -->
<xs:element name ="Method">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:enumeration value="Cone Calorimeter"/>
            <xs:enumeration value="Furniture Calorimeter"/>
            <xs:enumeration value="Room/Corner"/>
            <xs:enumeration value="LIFT Apparatus"/>
            <xs:enumeration value="Ignitability Apparatus"/>
            <xs:enumeration value="Other"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- The test standard element -->
<xs:element name ="Standard">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:enumeration value="ASTM E 1321-97a"></xs:enumeration>
            <xs:enumeration value="NT FIRE 032"></xs:enumeration>
            <xs:enumeration value="ASTM E 1537-02"></xs:enumeration>
            <xs:enumeration value="BS 476: Part 13: 1987"></xs:enumeration>
            <xs:enumeration value="ISO 9705:1993(E)"></xs:enumeration>
            <xs:enumeration value="NONE"></xs:enumeration>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- The references element must contain 0 or more reference elements -->
<xs:element name ="References">
    <xs:complexType>
        <xs:sequence>

```

```

        <xs:element ref = "Reference" minOccurs="0" maxOccurs="unbounded"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<!-- The reference element -->
<xs:element name = "Reference">
    <xs:complexType>
        <xs:sequence>
            <xs:element name = "RefID" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Authors" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Document" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Title" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "RefType" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Year" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Volume" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Number" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Page" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name = "Link" type="xs:anyURI" minOccurs="1" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<!-- The data element containing 10 different data groups for the 5 types of fire test allowed
by the UCFIRE schema -->
<xs:element name = "Data">
    <xs:complexType>
        <xs:sequence>
            <xs:element ref="TESTPARAMETERS" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="MATERIALS" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="TIME" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="TIMESERIES" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="OTHERSERIES" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="LIFTPARAMETERS" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="IGNITABILITYPARAMETERS" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="IMAGES" minOccurs="0" maxOccurs="1"></xs:element>

```

```

        <xs:element ref="VIDEOS" minOccurs="0" maxOccurs="1"></xs:element>
        <xs:element ref="OBSERVATIONS" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<!-- Indicates whether the specified value(s) or media are visible to the public. Only applicable
      when accessed through WEBFIRE -->
<xs:element name="Status">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="Public"/>
            <xs:enumeration value="Private"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- Child elements of the data element -->

<!-- ALPHA -->
<!-- The thermal diffusivity of the specimen -->
<xs:element name="ALPHA">
    <xs:complexType>
        <xs:sequence >
            <xs:element name="ALPHA_Value" type="xs:string"></xs:element>
            <xs:element ref="ALPHA_Units"></xs:element>
            <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="ALPHA_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>

```

```

        <xs:enumeration value="m^2/s"/>
    </xs:restriction>
</xs:simpleType>
</xs:element>

<!-- AREA -->
<!-- The AREA of the specified material -->
<xs:element name="AREA">
    <xs:complexType>
        <xs:sequence >
            <xs:element name="AREA_Value" type="xs:string"></xs:element>
            <xs:element ref="AREA_Units"></xs:element>
            <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="AREA_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="m^2"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- AMBHUMIDITY -->
<!-- The relative ambient humidity when conducting the test -->
<xs:element name="AMBHUMIDITY">
    <xs:complexType>
        <xs:sequence>
            <xs:element name="AMBHUMIDITY_Value" type="xs:string"></xs:element>
            <xs:element ref="AMBHUMIDITY_Units"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

```

```

<xs:element name ="AMBHUMIDITY_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="%" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- AMBTEMP -->
<!-- The ambient temeptrature when conducting the test -->
<xs:element name ="AMBTEMP">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="AMBTEMP_Value" type="xs:string"></xs:element>
      <xs:element ref ="AMBTEMP_Units"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="AMBTEMP_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="K" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- B-LIFT-->
<!-- LIFT Ignition paramter (Ignition correlation parameter); relevant only to the LIFT Test -->
<xs:element name ="B-LIFT">
  <xs:complexType>
    <xs:sequence>
      <xs:element name ="B-LIFT_Value" type="xs:string"></xs:element>

```



```

        <xs:element ref = "B-LIFT_Units" ></xs:element>
        <xs:element name = "ReductionMethod" type = "xs:string" minOccurs = "0" maxOccurs = "1" ></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name = "B-LIFT_Units">
    <xs:simpleType>
        <xs:restriction base = "xs:string">
            <xs:whiteSpace value = "collapse" ></xs:whiteSpace>
            <xs:enumeration value = "s^-0.5" />
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- C-LIFT-->
<!-- LIFT Ignition paramter (Flame heat transfer factor); relevant only to the LIFT Test -->
<xs:element name = "C-LIFT">
    <xs:complexType>
        <xs:sequence>
            <xs:element name = "C-LIFT_Value" type = "xs:string" ></xs:element>
            <xs:element ref = "C-LIFT_Units" ></xs:element>
            <xs:element name = "ReductionMethod" type = "xs:string" minOccurs = "0" maxOccurs = "1" ></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name = "C-LIFT_Units">
    <xs:simpleType>
        <xs:restriction base = "xs:string">
            <xs:whiteSpace value = "collapse" ></xs:whiteSpace>
            <xs:enumeration value = "s^0.5*m^1.5*(kW)^-1" />
        </xs:restriction>
    </xs:simpleType>
</xs:element>

```

```

<!-- CHUMIDITY -->
<!-- The realtive humdiduity used when conditioning the specified material -->
<xs:element name ="CHUMIDITY">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="CHUMIDITY_Value" type="xs:string"></xs:element>
      <xs:element ref ="CHUMIDITY_Units"></xs:element>
      <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="CHUMIDITY_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="%"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- CTEMP -->
<!-- The conditioning temperature of the specified material -->
<xs:element name ="CTEMP">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="CTEMP_Value" type="xs:string"></xs:element>
      <xs:element ref ="CTEMP_Units"></xs:element>
      <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="CTEMP_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">

```

```

        <xs:whiteSpace value="collapse"></xs:whiteSpace>
        <xs:enumeration value="K"/>
    </xs:restriction>
</xs:simpleType>
</xs:element>

<!-- COLOUR -->
<!-- The colour of the specified material -->
<xs:element name ="COLOUR">
    <xs:complexType>
        <xs:sequence>
            <xs:element name ="COLOUR_Value" type="xs:string"></xs:element>
            <xs:element ref ="COLOUR_Units"></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name ="COLOUR_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="-"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- CONDUCTIVITY -->
<!-- The thermal conductivity of the specified material -->
<xs:element name ="CONDUCTIVITY">
    <xs:complexType>
        <xs:sequence >
            <xs:element name ="CONDUCTIVITY_Value" type="xs:string"></xs:element>
            <xs:element ref ="CONDUCTIVITY_Units"></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
        </xs:sequence>

```

```

    </xs:complexType>
</xs:element>

<xs:element name ="CONDUCTIVITY_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m*K"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- ROOMCONFIGURATION -->
<!-- The configuration of the furniture calorimeter test room; relevant only to the FURN Test -->
<xs:element name ="ROOMCONFIGURATION">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="A"/>
      <xs:enumeration value="B"/>
      <xs:enumeration value="C"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- DENSITY -->
<!-- The density of the specified material -->
<xs:element name ="DENSITY">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="DENSITY_Value" type="xs:string"></xs:element>
      <xs:element ref ="DENSITY_Units"></xs:element>
      <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

<xs:element name ="DENSITY_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kg/m^3"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- DIAMETER -->
<!-- The diameter of the specified material -->
<xs:element name ="DIAMETER">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="DIAMETER_Value" type="xs:string"></xs:element>
      <xs:element ref ="DIAMETER_Units"></xs:element>
      <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="DIAMETER_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- EXHAUSTFLOWRATE -->
<!-- Exhaust system flow rate -->
<xs:element name ="EXHAUSTFLOWRATE">
  <xs:complexType>
    <xs:sequence >

```

```

        <xs:element name ="EXHAUSTFLOWRATE_Value"></xs:element>
        <xs:element ref ="EXHAUSTFLOWRATE_Units"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name ="EXHAUSTFLOWRATE_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="m^3/s"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- HEIGHT -->
<!-- The height of the specified material -->
<xs:element name ="HEIGHT">
    <xs:complexType>
        <xs:sequence >
            <xs:element name ="HEIGHT_Value" type="xs:string"></xs:element>
            <xs:element ref ="HEIGHT_Units"></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name ="HEIGHT_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="m"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

```

```

<!-- HEATINGFLUX -->
<!-- The external heating flux the specimen is exposed to during the test; relevant to the CONE and
      LIFT test. Note in the LIFT test this flux is measured at the 50mm position. -->
<xs:element name="HEATINGFLUX">
  <xs:complexType>
    <xs:sequence >
      <xs:element name="HEATINGFLUX_Value" type="xs:string"></xs:element>
      <xs:element ref="HEATINGFLUX_Units"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="HEATINGFLUX_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- IGNTYPE -->
<!-- The ignition type used in the test; relevant to the FURN Test-->
<xs:element name="IGNTYPE">
  <xs:complexType>
    <xs:sequence >
      <xs:element ref="IGNTYPE_Value"></xs:element>
      <xs:element ref="IGNTYPE_Units"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="IGNTYPE_Value">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>

```

```

        <xs:enumeration value="SPARK"/>
        <xs:enumeration value="PILOT FLAME"/>
        <xs:enumeration value="NONE"/>
    </xs:restriction>
</xs:simpleType>
</xs:element>

<xs:element name="IGNTYPE_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"/></xs:whiteSpace>
            <xs:enumeration value="-"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- INITIALMASS -->
<!-- Initial mass of the specified material -->
<xs:element name="INITIALMASS">
    <xs:complexType>
        <xs:sequence >
            <xs:element name="INITIALMASS_Value" type="xs:string"/></xs:element>
            <xs:element ref="INITIALMASS_Units"/></xs:element>
            <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"/></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="INITIALMASS_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"/></xs:whiteSpace>
            <xs:enumeration value="kg"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

```



```

<!-- FINALMASS -->
<!-- Final mass of the speciifed material -->
<xs:element name="FINALMASS">
  <xs:complexType>
    <xs:sequence >
      <xs:element name="FINALMASS_Value" type="xs:string"></xs:element>
      <xs:element ref="FINALMASS_Units"></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="FINALMASS_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kg"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- Images -->
<!-- Images related to the experiment -->
<xs:element name="IMAGES">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="IMAGE" minOccurs="1" maxOccurs="unbounded"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="IMAGE">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="ID" type="xs:decimal"></xs:element>

```

```

        <xs:element name ="Description" type="xs:string"></xs:element>
        <xs:element name ="FileName" type="xs:string"></xs:element>
        <xs:element ref ="Status"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<!-- KPC-->
<!-- The thermal inertia of the specimen; relevant to the LIFT test/experiment and the materials group -->
<xs:element name ="KPC">
    <xs:complexType>
        <xs:sequence>
            <xs:element name ="KPC_Value" type="xs:string"></xs:element>
            <xs:element ref ="KPC_Units" ></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
            <xs:element name ="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name ="KPC_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="kW^2*s/m^4*K^2"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- H-->
<!-- The heat loss coefficient; relevant only to the LIFT Test-->
<xs:element name ="H">
    <xs:complexType>
        <xs:sequence>
            <xs:element name ="H_Value" type="xs:string"></xs:element>
            <xs:element ref ="H_Units"></xs:element>

```

```

        <xs:element name ="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name ="H_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="kW/m^2"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- IGNITABILITYPARAMETERS -->
<!-- The parameters derived from the ignitability test -->
<xs:element name="IGNITABILITYPARAMETERS">
    <xs:complexType>
        <xs:sequence>
            <xs:element ref ="KPC"></xs:element>
            <xs:element ref ="QCRIT"></xs:element>
            <xs:element ref ="THERMALPROPERTIES"></xs:element>
            <xs:element ref ="TIG"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<!-- LENGTH -->
<!-- The length of the specified material -->
<xs:element name ="LENGTH">
    <xs:complexType>
        <xs:sequence >
            <xs:element name ="LENGTH_Value" type="xs:string"></xs:element>
            <xs:element ref ="LENGTH_Units"></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

```

```

    </xs:complexType>
</xs:element>

<xs:element name="LENGTH_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- LIFT Paramters -->
<xs:element name="LIFTPARAMETERS">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="B-LIFT"></xs:element>
      <xs:element ref="C-LIFT"></xs:element>
      <xs:element ref="H"></xs:element>
      <xs:element ref="KPC"></xs:element>
      <xs:element ref="PHI"></xs:element>
      <xs:element ref="QCRIT"></xs:element>
      <xs:element ref="QMIN0"></xs:element>
      <xs:element ref="QMIN1"></xs:element>
      <xs:element ref="QS"></xs:element>
      <xs:element ref="TIG"></xs:element>
      <xs:element ref="TS"></xs:element>
      <xs:element ref="TSTAR"></xs:element>
      <xs:element ref="VF"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<!-- MASSLOSS -->
<!-- The effective massloss of the specified material -->
<xs:element name="MASSLOSS">

```

```

<xs:complexType>
  <xs:sequence >
    <xs:element name ="MASSLOSS_Value" type="xs:string"></xs:element>
    <xs:element ref ="MASSLOSS_Units"></xs:element>
    <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
  </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name ="MASSLOSS_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="%" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- MATERIALS -->
<!-- The materials involved in the test. Note Preparation gives details of how the specimen
      was prepared -->
<xs:element name ="MATERIALS">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref ="MATERIAL" minOccurs="1" maxOccurs="unbounded"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="MATERIAL">
  <xs:complexType>
    <xs:sequence>
      <xs:element name ="MaterialID" type ="xs:string"></xs:element>
      <xs:element name ="Description" type ="xs:string"></xs:element>
      <xs:element name ="Name" type ="xs:string"></xs:element>
      <xs:element name ="Location" type ="xs:string"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

<xs:element ref = "Status"></xs:element>
<xs:element name="Manufacturer" type = "xs:string" minOccurs="1" maxOccurs = "1"></xs:element>
<xs:element name="ManufacturersAddress" type = "xs:string" minOccurs="1" maxOccurs = "1"></xs:element>
<xs:element name = "SerialNumber" type="xs:string" minOccurs="1" maxOccurs = "1"></xs:element>
<xs:element name="DateSupplied" type = "xs:string" minOccurs="1" maxOccurs = "1"></xs:element>

<xs:element ref = "DIAMETER" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "LENGTH" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "WIDTH" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "THICKNESS" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "HEIGHT" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "AREA" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "VOLUME" minOccurs="0" maxOccurs="1"></xs:element>

<xs:element ref = "INITIALMASS" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "FINALMASS" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "MASSLOSS" minOccurs="0" maxOccurs="1"></xs:element>

<xs:element ref = "COLOUR" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "CHUMIDITY" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "CTEMP" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "ORIENTATION" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "MOUNT" minOccurs="0" maxOccurs="1"></xs:element>

<xs:element ref = "ALPHA" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "CONDUCTIVITY" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "DENSITY" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "MASSPUA" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "KPC" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "PHI" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "QCRIT" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "TIG" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element ref = "SPHEAT" minOccurs="0" maxOccurs="1"></xs:element>
<xs:element name = "PREPARATION" minOccurs="0" maxOccurs="1"></xs:element>
</xs:sequence>
</xs:complexType>

```

```

</xs:element>

<!-- MASSPUA -->
<!-- The mass per unit surface area of the specified material -->
<xs:element name ="MASSPUA">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="MASSPUA_Value" type="xs:string"></xs:element>
      <xs:element ref ="MASSPUA_Units"></xs:element>
      <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="MASSPUA_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kg/m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- MOUNT -->
<!-- The means of mounting the sample -->
<xs:element name ="MOUNT">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="MOUNT_Value" type="xs:string"></xs:element>
      <xs:element ref ="MOUNT_Units"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="MOUNT_Units">
  <xs:simpleType>

```

```

    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="-" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- Observations -->
<!-- Observations related to the experiment -->
<xs:element name="OBSERVATIONS">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="OBSERVATION" minOccurs="1" maxOccurs="unbounded"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="OBSERVATION">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="ID" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element name="Time" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element name="Details" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<!-- OPTICALDENSITY-->
<!-- The optical density -->
<xs:element name="OPTICALDENSITY">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="OPTICALDENSITY _Value" type="xs:string"></xs:element>
      <xs:element ref="OPTICALDENSITY _Units"></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```



```

    </xs:complexType>
</xs:element>

<xs:element name=" OPTICALDENSITY _Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m^-1"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- OTHERSERIES-->
<!-- Contains dual series which are not a function of time -->
<xs:element name="OTHERSERIES">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="OtherSeries" minOccurs="1" maxOccurs="unbounded"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="OtherSeries">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="XName" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element ref="YName" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="ID" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="Description" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="Location" type="xs:string" minOccurs="1" maxOccurs="1" ></xs:element>
      <xs:element ref="Status" minOccurs="1" maxOccurs="1" ></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
      <xs:element name="XValues" type="xs:string" minOccurs="1" maxOccurs="1" ></xs:element>
      <xs:element name="YValues" type="xs:string" minOccurs="1" maxOccurs="1" ></xs:element>
      <xs:element name="AVG" type="xs:string" minOccurs="1" maxOccurs="1" ></xs:element>
      <xs:element name="MAX" type="xs:string" minOccurs="1" maxOccurs="1" ></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

    <xs:element name="TIGN" minOccurs="0" maxOccurs="1" ></xs:element>

    <xs:element ref="XUnits" minOccurs="1" maxOccurs="1" ></xs:element>
    <xs:element ref="YUnits" minOccurs="1" maxOccurs="1" ></xs:element>
  </xs:sequence>
</xs:complexType>
</xs:element>

<!-- Substitution groups linking common TimeSeries and Otherseries elements -->
<xs:element name="YName" substitutionGroup="Name"></xs:element>
<xs:element name="XName" substitutionGroup="Name"></xs:element>
<xs:element name="XUnits" substitutionGroup="Units"></xs:element>
<xs:element name="YUnits" substitutionGroup="Units"></xs:element>

<xs:element name="Name">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>

      <xs:enumeration value="DISTANCE"/>
      <xs:enumeration value="EXTCOEFF"/>
      <xs:enumeration value="FLUX"/>
      <xs:enumeration value="fCO"/>
      <xs:enumeration value="fCO2"/>
      <xs:enumeration value="fH2O"/>
      <xs:enumeration value="fHBR"/>
      <xs:enumeration value="fHCL"/>
      <xs:enumeration value="fHCN"/>
      <xs:enumeration value="fSOOT"/>
      <xs:enumeration value="FLAMEFRONT"/>
      <xs:enumeration value="HC"/>
      <!-- <xs:enumeration value="HCPUA"/> -->
      <xs:enumeration value="HRR"/>
      <xs:enumeration value="HRRPUA"/>
      <xs:enumeration value="HRRTOT"/>
      <xs:enumeration value="HRRTOTPUA"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

```

```

<xs:enumeration value="MASS" />
<xs:enumeration value="MASSFLOW" />
<xs:enumeration value="MLR" />
<xs:enumeration value="MLRPUA" />
<xs:enumeration value="OPTICALDENSITY" />
<xs:enumeration value="PRESSURE" />
<xs:enumeration value="RSR" />
<xs:enumeration value="SEA" />
<xs:enumeration value="TSR" />
<xs:enumeration value="TEMPERATURE" />
<xs:enumeration value="TIME" />
<xs:enumeration value="VOLFLOW" />
<xs:enumeration value="XCO" />
<xs:enumeration value="XCO2" />
<xs:enumeration value="XCO/XCO2" />
<xs:enumeration value="XH2O" />
<xs:enumeration value="XHBR" />
<xs:enumeration value="XHCL" />
<xs:enumeration value="XHCN" />
<xs:enumeration value="XNOX" />
<xs:enumeration value="XO2" />
<xs:enumeration value="XSOOT" />

<!-- LIFT derived Otherseries -->
<xs:enumeration value="SQRT(t)" />
<xs:enumeration value="TIME^-1" />
<xs:enumeration value="TIME^-0.5" />
<xs:enumeration value="TIME^-1/1.5" />
<xs:enumeration value="INV_SQRT(t)" />
<xs:enumeration value="Normalized FLUX" />
<xs:enumeration value="POSITION" />
<xs:enumeration value="Qe(x)F(t)" />
<xs:enumeration value="V^-0.5" />
</xs:restriction>
</xs:simpleType>
</xs:element>

```

```

<xs:element name="Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"/></xs:whiteSpace>
      <xs:enumeration value="m"/>
      <xs:enumeration value="m^-1"/>

      <xs:enumeration value="kg/kg"/>
      <xs:enumeration value="MJ/kg"/>
      <!-- <xs:enumeration value="MJ/kg*m^2"/>-->
      <xs:enumeration value="kW"/>
      <xs:enumeration value="kW/m^2"/>

      <xs:enumeration value="MJ"/>
      <xs:enumeration value="MJ/m^2"/>
      <xs:enumeration value="kg"/>
      <xs:enumeration value="kg/s"/>
      <xs:enumeration value="kg/m^2*s"/>
      <xs:enumeration value="-"/>
      <xs:enumeration value="Pa"/>
      <xs:enumeration value="m^2/s"/>
      <xs:enumeration value="m^2/kg"/>
      <xs:enumeration value="m^2"/>
      <xs:enumeration value="K"/>
      <xs:enumeration value="s"/>
      <xs:enumeration value="m^3/s"/>

      <xs:enumeration value="°"/>
      <xs:enumeration value="ppm"/>

      <xs:enumeration value="kg/m^2"/>

      <!-- LIFT Parameters-->
      <xs:enumeration value="s^0.5"/>
      <xs:enumeration value="s^-1"/>

```

```

        <xs:enumeration value="s^-0.5"/>
        <xs:enumeration value="s^-1/1.5"/>
        <xs:enumeration value="m^-0.5*s^0.5"/>
    </xs:restriction>
</xs:simpleType>
</xs:element>

<!-- ORIENTATION-->
<!-- The orientation of the specimen -->
<xs:element name="ORIENTATION">
    <xs:complexType>
        <xs:sequence >
            <xs:element ref="ORIENTATION_Value"></xs:element>
            <xs:element ref="ORIENTATION_Units"></xs:element>
            <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="ORIENTATION_Value">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="Horizontal"/>
            <xs:enumeration value="Vertical"/>
            <xs:enumeration value="horizontal"/>
            <xs:enumeration value="vertical"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<xs:element name="ORIENTATION_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="-"/>

```

```

        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- PHI-->
<!-- The flame heating parameter; relevant only to the LIFT Test and materials group -->
<xs:element name ="PHI">
    <xs:complexType>
        <xs:sequence>
            <xs:element name ="PHI_Value" type="xs:string"></xs:element>
            <xs:element ref ="PHI_Units" ></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
            <xs:element name ="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name ="PHI_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="kW^2/m^3"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- PREPARATION-->
<!-- The how the specimen was prepared for the fire test -->
<xs:element name ="PREPARATION">
    <xs:complexType>
        <xs:sequence >
            <xs:element name ="PREPARATION_Value" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref ="PREPARATION_Units"></xs:element>
            <xs:element name ="Link" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>

```

```

</xs:element>

<xs:element name="PREPARATION_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="-" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- QCRIT-->
<!-- The critical flux for ignition; relevant only to the LIFT and IGNITABILITY Tests and the materials group -->
<xs:element name="QCRIT">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="QCRIT_Value" type="xs:string"></xs:element>
      <xs:element ref="QCRIT_Units"></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="QCRIT_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m^2" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- QMIN0-->
<!-- The minimum flux for ignition from ignition data; relevant only to the LIFT Test -->
<xs:element name="QMIN0">

```

```

<xs:complexType>
  <xs:sequence>
    <xs:element name ="QMIN0_Value" type="xs:string"></xs:element>
    <xs:element ref ="QMIN0_Units" ></xs:element>
    <xs:element name ="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
  </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name ="QMIN0_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- QMIN1-->
<!-- The minimum flux for ignition from flame spread data; relevant only to the LIFT Test -->
<xs:element name ="QMIN1">
  <xs:complexType>
    <xs:sequence>
      <xs:element name ="QMIN1_Value" type="xs:string"></xs:element>
      <xs:element ref ="QMIN1_Units" ></xs:element>
      <xs:element name ="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="QMIN1_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

```



```

    </xs:simpleType>
</xs:element>

<!-- QSMIN-->
<!-- The minimum flux for flame spread; relevant only to the LIFT Test -->
<xs:element name="QS">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="QS_Value" type="xs:string"></xs:element>
      <xs:element ref="QS_Units" ></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="QS_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kW/m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- SPHEAT -->
<!-- The specific heat of the specimen -->
<xs:element name="SPHEAT">
  <xs:complexType>
    <xs:sequence >
      <xs:element name="SPHEAT_Value" type="xs:string"></xs:element>
      <xs:element ref="SPHEAT_Units"></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

<xs:element name ="SPHEAT_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="kJ/m^3*K"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- SURFACEAREA -->
<!-- The ignition type used in the test; relevant to the FURN Test-->
<xs:element name ="SURFACEAREA">
  <xs:complexType>
    <xs:sequence >
      <xs:element name ="SURFACEAREA_Value" type="xs:string"></xs:element>
      <xs:element ref ="SURFACEAREA_Units"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="SURFACEAREA_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m^2"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- THERMALPROPERTIES-->
<!-- The thermal properties of the specimen -->
<xs:element name ="THERMALPROPERTIES">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref ="THERMALPROPERTIES_Value"></xs:element>

```

```

        <xs:element ref = "THERMALPROPERTIES_Units" ></xs:element>
        <xs:element name = "Link" type="xs:string" minOccurs = "0" maxOccurs="1"></xs:element>
        <xs:element name = "ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name = "THERMALPROPERTIES_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="NA"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<xs:element name = "THERMALPROPERTIES_Value">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="Thermally Thin"/>
            <xs:enumeration value="Thermally Thick"/>
            <xs:enumeration value="Thermally Intermediate"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- THICKNESS -->
<!-- The thickness of the specified material -->
<xs:element name = "THICKNESS">
    <xs:complexType>
        <xs:sequence >
            <xs:element name = "THICKNESS_Value" type="xs:string"></xs:element>
            <xs:element ref = "THICKNESS_Units"></xs:element>
            <xs:element name = "Link" type="xs:string" minOccurs = "0" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

```

```

    </xs:complexType>
</xs:element>

<xs:element name="THICKNESS_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- TESTPARAMETERS -->
<!-- The conditions of the test -->
<xs:element name="TESTPARAMETERS">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="AMBHUMIDITY" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="AMBTTEMP" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="EXHAUSTFLOWRATE" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="HEATINGFLUX" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="IGNTYPE" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="ROOMCONFIGURATION" minOccurs="0" maxOccurs="1"></xs:element>
      <xs:element ref="SURFACEAREA" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<!-- TIG -->
<!-- The minimum temperature for ignition; relevant to the LIFT and IGNITABILITY Tests and the materials group -->
<xs:element name="TIG">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TIG_Value" type="xs:string"></xs:element>
      <xs:element ref="TIG_Units" ></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

```

```

        <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
</xs:complexType>
</xs:element>

<xs:element name="TIG_Units">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="K"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

<!-- Time -->
<!-- The time component of the time series -->
<xs:element name="TIME">
    <xs:complexType>
        <xs:sequence>
            <xs:element name="Values" type="xs:string" minOccurs="1" maxOccurs="1"></xs:element>
            <xs:element name="FLAMEOUT" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element name="FLASHOVER" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element name="TIGN" minOccurs="0" maxOccurs="1"></xs:element>
            <xs:element ref="TUnits" minOccurs="1" maxOccurs="1"></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="TUnits">
    <xs:simpleType>
        <xs:restriction base="xs:string">
            <xs:whiteSpace value="collapse"></xs:whiteSpace>
            <xs:enumeration value="s"/>
        </xs:restriction>
    </xs:simpleType>
</xs:element>

```

```

<xs:element name="TIMESERIES">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="TimeSeries" minOccurs="1" maxOccurs="unbounded"/></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="TimeSeries">
  <xs:complexType>
    <xs:sequence>
      <xs:element ref="Name" maxOccurs="1" minOccurs="1"/></xs:element>
      <xs:element name="ID" type="xs:string" maxOccurs="1" minOccurs="1"/></xs:element>
      <xs:element name="Description" type="xs:string" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element name="Location" type="xs:string" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element ref="Status" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="1" maxOccurs="1"/></xs:element>
      <xs:element name="Values" type="xs:string" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element name="AVG" type="xs:string" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element name="CONEAVG" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="AVG60S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="AVG180S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="AVG300S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="MAX" type="xs:string" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element name="CONEAVG" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="MAX60S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="MAX180S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="MAX300S" type="xs:string" minOccurs="0" maxOccurs="1" /></xs:element>
      <xs:element name="TIMEOFMAX" minOccurs="1" maxOccurs="1" /></xs:element>
      <xs:element ref="Units" minOccurs="1" maxOccurs="1"/></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<!-- TS -->

```

```

<!-- The minimum temperature for flame spread; relevant only to the LIFT Test -->
<xs:element name="TS">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TS_Value" type="xs:string"/></xs:element>
      <xs:element ref="TS_Units" /></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"/></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="TS_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"/></xs:whiteSpace>
      <xs:enumeration value="K"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- TSTAR -->
<!-- The characteristic equilibrium or thermal steady state time; relevant only to the LIFT Test -->
<xs:element name="TSTAR">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="TSTAR_Value" type="xs:string"/></xs:element>
      <xs:element ref="TSTAR_Units" /></xs:element>
      <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"/></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="TSTAR_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"/></xs:whiteSpace>

```

```

        <xs:enumeration value="s"/>
    </xs:restriction>
</xs:simpleType>
</xs:element>

<!-- Videos -->
<!-- Videos related to the experiment -->
<xs:element name="VIDEOS">
    <xs:complexType>
        <xs:sequence>
            <xs:element ref="VIDEO" minOccurs="1" maxOccurs="unbounded"/></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<xs:element name="VIDEO">
    <xs:complexType>
        <xs:sequence>
            <xs:element name="ID" type="xs:decimal"/></xs:element>
            <xs:element name="Description" type="xs:string"/></xs:element>
            <xs:element name="FileName" type="xs:string"/></xs:element>
            <xs:element ref="Status"/></xs:element>
        </xs:sequence>
    </xs:complexType>
</xs:element>

<!-- VF -->
<!-- The flame spread velcoity; relevant only to the LIFT Test -->
<xs:element name="VF">
    <xs:complexType>
        <xs:sequence>
            <xs:element name="VF_Value" type="xs:string"/></xs:element>
            <xs:element ref="VF_Units"/></xs:element>
            <xs:element name="ReductionMethod" type="xs:string" minOccurs="0" maxOccurs="1"/></xs:element>
        </xs:sequence>
    </xs:complexType>

```



```

</xs:element>

<xs:element name="VF_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m/s"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- VOLUME -->
<!-- The volume of the specified material -->
<xs:element name="VOLUME">
  <xs:complexType>
    <xs:sequence >
      <xs:element name="VOLUME_Value" type="xs:string"></xs:element>
      <xs:element ref="VOLUME_Units"></xs:element>
      <xs:element name="Link" type="xs:string" minOccurs="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name="VOLUME_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m^3"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

<!-- WIDTH -->
<!-- The width of the specified material -->
<xs:element name="WIDTH">
  <xs:complexType>

```

```

    <xs:sequence >
      <xs:element name ="WIDTH_Value" type="xs:string"></xs:element>
      <xs:element ref ="WIDTH_Units"></xs:element>
      <xs:element name ="Reference" type="xs:string" minOccurs ="0" maxOccurs="1"></xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>

<xs:element name ="WIDTH_Units">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:whiteSpace value="collapse"></xs:whiteSpace>
      <xs:enumeration value="m"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>

</xs:schema>

```

# Appendix C: Exemplar Excel Workbook

Microsoft Excel - C7S1

File Edit View Insert Format Tools Data Window Help

Type a question for help

B3 C7S1

Undo

	A	B	C	D	E	F	G	H
1	Summary							
2								
3	TestID:	C7S1						
4	Description:	Chair C7S1 Single seater chair						
5	Method:	Furniture Calorimeter						
6	Standard:	ASTM E 1537-02						
7	TestDate:	2/05/1999						
8								
9	Details							
10								
11	Description:							
12	TestSeriesID:							
13	TestNumber:							
14	NumberOfTests:							
15	TestOperator:							
16	TestOrganization:	UOC						
17	OrganisationsAddress:	Christchurch, New Zealand						
18	TestSponsor:							
19	SponsorsAddress:							
20	TestRequester:							
21	RequestersAddress:							
22								
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.

Ready

Microsoft Excel - C7S1.xls													
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B3 60													
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Parameter	Value	Units	Options									
2													
3	AMBHUMIDITY	60	%										
4	AMBTMP	283	K										
5	EXHAUSTFLOWRATE		m^3/s										
6	HEATINGFLUX		kW/m^2										
7	IGNTYPE		-	CRIB, SPARK, NONE									
8	SURFACEAREA		m^2										
9													
10	FLAMEOUT		s										
11	FLASHOVER		s										
12	TIGN		s										
13													
14	LIFT Test Parameters												
15													
16	Preheat Time		s										
17	Preheat Time		s										
18	Preheat Time		s										
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Microsoft Excel - C7S1

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A2

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Description	Name	Location	Status		Manufacturer	ManufacturersAddress	SerialNumber	DateSupplied		DIAMETER (m)	LENGTH (m)			
2															
3															
4															
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.

Ready

Microsoft Excel - C7S1											
File Edit View Insert Format Tools Data Window Help											
Type a question for help											
Arial 10 B I U											
C1 TIME											
	A	B	C	D	E	F	G	H	I	J	K
1	Time Series:		TIME	HRR	XO2	XCO2	XCO	PRESSURE	TEMPERATURE	MASS	MASSFLOW
2	Description:		Description	Calculated	Molar Fraction	Molar Fraction	Molar Fraction	BiDi Probe	Duct Temperature	Scale Mass	Calculated
3	Location:			Duct	Duct	Duct	Duct	Duct	Duct	Platform	Duct
4	Reduction Method:			NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
5	Status:		Public	Public	Public	Public	Public	Public	Public	Public	Public
6	Units:		s	kW	-	-	ppm	Pa	K	kg	kg/s
7			-180	0.5	0.2096	0.000353116	7	144	283	23.592	4.5
8			-178.9	0.9	0.2095	0.000353116	7	136	283	23.592	4.5
9			-177.8	0.5	0.2094	0.000361335	7	143	283	23.592	4.5
10			-176.7	0.5	0.2096	0.000353116	7	134	283	23.592	4.54
11			-175.5	-0.9	0.2095	0.000353116	8	136	283	23.592	4.54
12			-174.4	-0.3	0.2096	0.000353116	6	156	283	23.442	4.59
13			-173.3	1.8	0.2094	0.000361335	7	136	283	23.592	4.61
14			-172.2	1.7	0.2095	0.000361335	8	157	283	23.592	4.63
15			-171	1	0.2094	0.000378457	7	142	283	23.592	4.53
16			-169.9	1.6	0.2095	0.000361335	4	143	283	23.592	4.51
17			-168.8	-1	0.2095	0.000361335	8	125	283	23.442	4.49
18			-167.7	-0.4	0.2095	0.000353116	6	130	283	23.592	4.5
19			-166.6	-0.3	0.2095	0.000361335	8	151	283	23.442	4.54
20			-165.5	3.4	0.2095	0.000370238	13	143	283	23.592	4.65
21			-164.5	3.6	0.2095	0.000378457	8	158	283	23.442	4.71
22			-163.4	5.6	0.2094	0.000370238	8	157	283	23.592	4.7
23			-162.3	2.5	0.2095	0.000378457	7	152	283	23.592	4.71
24			-161.1	1.8	0.2095	0.000361335	7	146	283	23.442	4.62
25			-160	-2.8	0.2095	0.000370238	8	145	283	23.592	4.52
26			-158.9	-4.9	0.2097	0.000361335	6	129	283	23.442	4.52
27			-157.8	-4	0.2094	0.000370238	8	126	282	23.442	4.5
28			-156.7	-2.3	0.2095	0.000361335	7	153	283	23.442	4.49
29			-155.6	-3.4	0.2093	0.000378457	6	140	283	23.592	4.5
30			-154.5	-3.9	0.2095	0.000378457	6	142	283	23.592	4.58
31			-153.4	-3.1	0.2095	0.000370238	6	133	283	23.592	4.58
32			-152.4	-5	0.2095	0.000378457	6	149	283	23.592	4.62
33			-151.3	-4	0.2095	0.000370238	7	153	283	23.592	4.6
Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.											
Ready											



Microsoft Excel - MW_MDF														
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Type a question for help														
Arial 10 B I U														
A1 Other Series:														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Other Series:		FLUX	TIME		DISTANCE	FLUX		FLAMEFRONT	TIME		FLAMEFRONT	TIME	
2	Description:		IgnitionData	IgnitionData		FluxProfile	FluxProfile		FlameSpreadData 0	FlameSpreadData 0		FlameSpreadData 1	FlameSpreadData 1	
3	Location:		Specimen	Specimen		Specimen	Specimen		Specimen	Specimen		Specimen	Specimen	
4	Status:		Public	Public		Public	Public		Public	Public		Public	Public	
5	Units:		kW/m^2	s		m	kW/m^2		m	s		m	s	
6			12.500	No ign.		0.050	24.198		0.000	479.000		0.000	478.000	
7			15.000	No ign.		0.100	23.746		0.025	479.000		0.025	478.000	
8			17.500	409.000		0.150	22.000		0.050	479.000		0.050	478.000	
9			20.000	309.000		0.200	19.822		0.075	479.000		0.075	478.000	
10			30.000	122.000		0.250	17.254		0.100	479.000		0.100	478.000	
11			40.000	73.000		0.300	14.445		0.125	479.000		0.125	478.000	
12			50.000	37.700		0.350	11.225		0.150	479.000		0.150	478.000	
13			60.000	25.400		0.400	8.052		0.175	479.000		0.175	478.000	
14						0.450	5.975		0.200	479.000		0.200	478.000	
15						0.500	3.912		0.225	482.000		0.225	478.000	
16						0.550	2.812		0.250	488.000		0.250	478.000	
17						0.600	1.912		0.275	492.000		0.275	487.000	
18						0.650	1.323		0.300	530.000		0.300	515.000	
19						0.700	0.917		0.325	576.000		0.325	556.000	
20						0.750	0.737		0.350	640.000		0.350	607.000	
21									0.375	708.000		0.375	687.000	
22									0.400	811.000		0.400	804.000	
23									0.425	942.000		0.425	927.000	
24									0.450	1134.000		0.441	1089.000	
25									0.460	1232.000				
26														
27														
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.														
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Microsoft Excel - C7S1

File Edit View Insert Format Tools Data Window Help

Type a question for help

B2 VIDEO

	A	B	C	D	E	F	G	H	I	J
1	Description	Type	Status	FilePath						
2	Chair Fire	VIDEO	Public	c:\Data\Example1.avi						
3	Chair Fire	IMAGE	Public	c:\Data\Example1.jpg						
4										
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.

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Microsoft Excel - DOT\_DomesticFoam

File Edit View Insert Format Tools Data Window Help

Type a question for help

B3 Details

	A	B
1	Observations	
2		
3	Time	Details
4	-	The test results relate only to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the products in use.
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.

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Microsoft Excel - C7S1										
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Type a question for help										
C4 University of Canterbury Research Report - PhD Thesis										
	A	B	C	D	E	F	G	H	I	
1	References									
2										
3	RefID	Authors	Document	Title	ReferenceType	Year	Volume	Number	Page	
4	1999/17	P A Enright	University of Canterbury Research Report - PhD Thesis	Heat Release and the Combustion Behaviour of Upholstered Furniture	Report	1999				http://w
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Main Parameters Materials TimeSeries OtherSeries Media Obs. Refs.										
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## Appendix D: ZM Method for the TR Correlation

```
Function ScrutiniseTRC (ByVal Data As DoubleVector) As DoubleVector
' Scrutinise the ignition correlation and remove data points that
violates the zero heat loss assumption.

Data = Algorithms.BubbleSort(Data)

Dim tol As Double = 5 / 100
Dim result As New DoubleVector
Dim x() As Double = Data.x
Dim y() As Double = Data.y
Dim ResidualError As Double
Dim x0() As Double
Dim y0() As Double
Dim ystar() As Double

' Check to see if the data is clustered.
Dim cluster As Boolean = False
For i As Integer = 0 To x.Length - 1
    For j As Integer = 0 To x.Length - 1
        If i <> j And x(i) = x(j) Then
            cluster = True
            Exit For
        End If
    Next
Next

' Calculate the required tolerance.
Dim ymax As Double = y(0)
For i As Integer = 0 To y.Length - 1
    If y(i) > ymax Then
        ymax = y(i)
    End If
Next

tol = tol * ymax

' Linear Regression.
Dim c As Double = Algorithms.LinearRegression(x, y, False).c
Dim m As Double = Algorithms.LinearRegression(x, y, False).m

ystar = Algorithms.zeros(x.Length - 1)
For j As Integer = 0 To x.Length - 1
    ystar(j) = m * x(j) + c
Next

' Calculate the mean residual error.
ResidualError = Algorithms.ResidualError(y, ystar)

x0 = x
y0 = y

While ResidualError > tol
    x0 = x
    y0 = y

    ' Remove a point, or cluster of points from the right.
```

```

If cluster = True Then

    Dim n1 As Integer = 0
    Dim xi As Double = x(x.Length - 1)
    Dim i As Integer = 0

    While x(i) = xi
        n1 = n1 + 1
        i = i - 1
    End While

    Dim tempx(x.Length - 1 - n1) As Double
    Dim tempy(y.Length - 1 - n1) As Double

    For j As Integer = 0 To x.Length - 1 - n1
        tempx(j) = x(j)
        tempy(j) = y(j)
    Next

    x = tempx
    y = tempy

Else
    Dim tempx(x.Length - 1 - 1) As Double
    Dim tempy(y.Length - 1 - 1) As Double
    For i As Integer = 0 To x.Length - 1 - 1
        tempx(i) = x(i)
        tempy(i) = y(i)
    Next
    x = tempx
    y = tempy

End If

' Linear Regression.
c = Algorithms.LinearRegression(x, y, False).c
m = Algorithms.LinearRegression(x, y, False).m

ystar = Algorithms.zeros(x.Length - 1)
For j As Integer = 0 To x.Length - 1
    ystar(j) = m * x(j) + c
Next

' Calculate the mean residual error.
ResidualError = Algorithms.ResidualError(y, ystar)

End While

result.x = x
result.y = y

Return result

End Function

```

## Appendix E: ZM Method for the CF Correlation

```
Function ScrutiniseLIFTIgnitionCorrelation2(ByVal Data As
DoubleVector) As DoubleVector
' Scrutinise the ignition correlation and remove data points that
violates the zero heat loss assumption.

Data = Algorithms.BubbleSort(Data)

Dim tol As Double = 5 / 100
Dim result As New DoubleVector

Dim x() As Double = Data.x
Dim y() As Double = Data.y
Dim ResidualError As Double

Dim x0() As Double
Dim y0() As Double
Dim ystar() As Double

' Check to see if the data is clustered.
Dim cluster As Boolean = False
For i As Integer = 0 To x.Length - 1
    For j As Integer = 0 To x.Length - 1
        If i <> j And x(i) = x(j) Then
            cluster = True
            Exit For
        End If
    Next
Next

' Calculate the required tolerance.
Dim ymax As Double = y(0)
For i As Integer = 0 To y.Length - 1
    If y(i) > ymax Then
        ymax = y(i)
    End If
Next
tol = tol * ymax

' Linear Regression
Dim c As Double = Algorithms.LinearRegression(x, y, True).c
Dim m As Double = Algorithms.LinearRegression(x, y, True).m

ystar = Algorithms.zeros(x.Length - 1)
For j As Integer = 0 To x.Length - 1
    ystar(j) = m * x(j) + c
Next

ResidualError = Algorithms.ResidualError(y, ystar)
Dim GOF As Double = Algorithms.RSquared(y, ystar)
Dim LastResidualError As Double = ResidualError
Dim LastGOF As Double = GOF
x0 = x
y0 = y
```

```

While ResidualError > tol
    x0 = x
    y0 = y
    LastResidualError = ResidualError
    LastGOF = GOF

    If cluster = True Then

        Dim n1 As Integer = 0
        Dim xi As Double = x(0)
        Dim i As Integer = 0

        While x(i) = xi
            n1 = n1 + 1
            i = i + 1
        End While

        Dim tempx(x.Length - 1 - n1) As Double
        Dim tempy(y.Length - 1 - n1) As Double
        For j As Integer = n1 To x.Length - 1
            tempx(j - n1) = x(j)
            tempy(j - n1) = y(j)
        Next
        x = tempx
        y = tempy

    Else
        Dim tempx(x.Length - 1 - 1) As Double
        Dim tempy(y.Length - 1 - 1) As Double
        For i As Integer = 1 To x.Length - 1
            tempx(i - 1) = x(i)
            tempy(i - 1) = y(i)
        Next
        x = tempx
        y = tempy
    End If

    ' Linear Regression
    c = Algorithms.LinearRegression(x, y, True).c
    m = Algorithms.LinearRegression(x, y, True).m

    ystar = Algorithms.zeros(x.Length - 1)
    For j As Integer = 0 To x.Length - 1
        ystar(j) = m * x(j) + c
    Next

    ResidualError = Algorithms.ResidualError(y, ystar)
    GOF = Algorithms.RSquared(y, ystar)

    If ResidualError > 1.05 * LastResidualError Or GOF < LastGOF Then
        x = x0
        y = y0
        c = Algorithms.LinearRegression(x, y, True).c
        m = Algorithms.LinearRegression(x, y, True).m
        Exit While
    End If

End While

```

```
result.x = x  
result.y = y  
  
Return result  
  
End Function
```

## Appendix F: ZM Method for the FS Correlation

```
Function ScrutiniseFlameSpreadCorrelation(ByVal Data As DoubleVector)
As DoubleVector
' Scrutinise the flamespread correlation and remove data points that
violates the zero heat loss assumption.

Data = Algorithms.BubbleSort(Data)

Dim tol As Double = 5 / 100
Dim result As New DoubleVector
Dim x() As Double = Data.x
Dim y() As Double = Data.y
Dim ResidualError As Double
Dim x0() As Double
Dim y0() As Double
Dim ystar() As Double

' Check to see if the data is clustered.
Dim cluster As Boolean = False
For i As Integer = 0 To x.Length - 1
    For j As Integer = 0 To x.Length - 1
        If i <> j And x(i) = x(j) Then
            cluster = True
            Exit For
        End If
    Next
Next

' Calculate the required tolerance.
Dim ymax As Double = y(0)
For i As Integer = 0 To y.Length - 1
    If y(i) > ymax Then
        ymax = y(i)
    End If
Next

tol = tol * ymax

' Linear Regression
Dim c As Double = Algorithms.LinearRegression(x, y, True).c
Dim m As Double = Algorithms.LinearRegression(x, y, True).m

ystar = Algorithms.zeros(x.Length - 1)
For j As Integer = 0 To x.Length - 1
    ystar(j) = m * x(j) + c
Next

ResidualError = Algorithms.ResidualError(y, ystar)
Dim GOF As Double = Algorithms.RSquared(y, ystar)
Dim LastResidualError As Double = ResidualError
Dim LastGOF As Double = GOF
x0 = x
y0 = y

Dim xleft() As Double
Dim yleft() As Double
Dim xright() As Double
Dim yright() As Double
```



```

Dim cleft As Double
Dim cright As Double
Dim mleft As Double
Dim mright As Double
Dim gleft As Double = GOF
Dim gright As Double = GOF
Dim ystarleft() As Double
Dim ystarright() As Double

Dim n1 As Integer = 0
Dim n2 As Integer = 0

While ResidualError > tol
    x0 = x
    y0 = y
    LastResidualError = ResidualError
    LastGOF = GOF

    ' Remove Data points from the left
    If cluster = True Then

        n1 = 1
        Dim xi As Double = x(0)
        Dim i As Integer = 1

        While x(i) = xi
            n1 = n1 + 1
            i = i + 1
        End While

        Dim tempx(x.Length - 1 - n1) As Double
        Dim tempy(y.Length - 1 - n1) As Double
        For j As Integer = n1 To x.Length - 1
            tempx(j - n1) = x(j)
            tempy(j - n1) = y(j)
        Next
        xleft = tempx
        yleft = tempy

    Else
        Dim tempx(x.Length - 1 - 1) As Double
        Dim tempy(y.Length - 1 - 1) As Double
        For i As Integer = 1 To x.Length - 1
            tempx(i - 1) = x(i)
            tempy(i - 1) = y(i)
        Next
        xleft = tempx
        yleft = tempy
    End If

    ' Linear Regression
    cleft = Algorithms.LinearRegression(xleft, yleft, True).c
    mleft = Algorithms.LinearRegression(xleft, yleft, True).m
    ystarleft = Algorithms.zeros(xleft.Length - 1)
    For j As Integer = 0 To xleft.Length - 1
        ystarleft(j) = mleft * xleft(j) + cleft
    Next

    Gleft = Algorithms.RSquared(yleft, ystarleft)

```

```

' Remove Data points from the right
If cluster = True Then

    n2 = 0
    Dim xi As Double = x(x.Length - 1)
    Dim i As Integer = x.Length - 1

    While x(i) = xi
        n2 = n2 + 1
        i = i - 1
    End While

    Dim tempx(x.Length - 1 - n2) As Double
    Dim tempy(y.Length - 1 - n2) As Double
    For j As Integer = 0 To x.Length - 1 - n2
        tempx(j) = x(j)
        tempy(j) = y(j)
    Next
    xright = tempx
    yright = tempy

Else
    Dim tempx(x.Length - 1 - 1) As Double
    Dim tempy(y.Length - 1 - 1) As Double
    For i As Integer = 0 To x.Length - 1 - 1
        tempx(i) = x(i)
        tempy(i) = y(i)
    Next
    xright = tempx
    yright = tempy
End If

' Linear Regression
cright = Algorithms.LinearRegression(xright, yright, True).c
mright = Algorithms.LinearRegression(xright, yright, True).m
ystarright = Algorithms.zeros(xright.Length - 1)

For j As Integer = 0 To xright.Length - 1
    ystarright(j) = mright * xright(j) + cright
Next

gright = Algorithms.RSquared(yright, ystarright)

' Update data
If Gleft > Gright Then
    x = xleft
    y = yleft
ElseIf gright >= gleft Then
    x = xright
    y = yright
Else
    Dim tempx(x.Length - 1 - n1 - n2) As Double
    Dim tempy(y.Length - 1 - n1 - n2) As Double
    For i As Integer = n1 To x.Length - 1 - n2
        tempx(i - n1) = x(i)
        tempy(i - n1) = y(i)
    Next
    x = tempx
    y = tempy
End If

```

```

' Linear Regression
c = Algorithms.LinearRegression(x, y, True).c
m = Algorithms.LinearRegression(x, y, True).m

ystar = Algorithms.zeros(x.Length - 1)
For j As Integer = 0 To x.Length - 1
    ystar(j) = m * x(j) + c
Next

ResidualError = Algorithms.ResidualError(y, ystar)
GOF = Algorithms.RSquared(y, ystar)

If ResidualError > 1.05 * LastResidualError Or GOF < LastGOF Then
    x = x0
    y = y0
    c = Algorithms.LinearRegression(x, y, True).c
    m = Algorithms.LinearRegression(x, y, True).m
    Exit While
End If

End While

result.x = x
result.y = y

Return result

End Function

```